PROCEEDINGS OF THE ROYAL SOCIETY OF QUEENSLAND

YACHATDAC

YUMBANGKU ABORIGINAL CULTURAL HERITAGE & TOURISM DEVELOPMENT ABORIGINAL CORPORATION

"Ancient Traditions Walking Together with Contemporary Visions"

2020 VOLUME 128

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VOLUME 128

PROCEEDINGS OF THE ROYAL SOCIETY OF QUEENSLAND

Editor: Angela H. Arthington

Special thanks are extended to the anonymous referees who reviewed papers submitted for publication in this volume of the *Proceedings*.

2020

The Royal Society of Queensland

Queensland's first scientific society
Established 1884

The Royal Society of Queensland

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His Excellency the Governor of Queensland
the Honourable Paul de Jersey AC

COVER ILLUSTRATION
YACHATDAC Logo and Banner
The Yumbangku Aboriginal Cultural Heritage and Tourism Development Aboriginal Corporation (YACHATDAC) based in Barcaldine has been formed by key members of the Traditional custodian families of the Iningai lands in Central West Queensland. Further information is available in the paper by Brown & Thompson (2020), 'Gracevale, a Case Study on Caring for Country and Rediscovery of Culture and Language by the Iningai People in Central West Queensland' (PRSQ 128, pp. 23–27).

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GOVERNOR OF QUEENSLAND

Message from the Governor of Queensland

As we navigate the challenges of COVID-19, I extend my support to all members of the Royal Society of Queensland.

The Society is justly proud of its long tradition of bringing together scientists and interested lay people to advance our understanding of the world, and I know Society members are saddened by the interruption to these engagements as we abide by social distancing. These dialogues and fora have played a significant role in the progress of science in our State. But even the most superficial survey of the Society's long and illustrious history reveals an organisation that has weathered many storms, emerging each time with renewed resolve to advance the cause of human understanding. It is my firm view that this will also be the case with the current situation.

I have been encouraged to see that many members of the Society have been able to continue their important work within the current limitations and note that many of the important collaborations promoted by the Society have been postponed rather than cancelled. I share with the members the hope they can be resumed as soon as it is safe to do so.

The emergence of the novel coronavirus has brought into sharper focus the critical importance of science to human flourishing. Yet science will continue to need advocates throughout the community, a need which the Royal Society remains uniquely qualified to fulfil. I remain immensely proud to serve as your Patron, and look forward to the time when we can meet again.

Paul de Jersey

His Excellency the Honourable Paul de Jersey AC
Governor of Queensland

The Royal Society of Queensland

The Royal Society of Queensland has an honourable history as the senior scientific institution in the state. It was established in 1884, with royal patronage continuing unbroken from 1885. The Governor of Queensland His Excellency The Honourable Paul de Jersey AC is the present Patron.

The Society seeks to increase respect for intellectual enquiry. It encourages original research and the application of evidence-based methods to policy development and decision making. The Society provides a forum for scientists and lay people to involve themselves in the progress of science in society, with 'science' defined broadly. As a non-partisan, secular, learned group, the Society is committed to the Enlightenment tradition of curiosity-led, knowledge-based enquiry that arguably was born with the Royal Society in London in 1660.

The centrepiece activity of the Society is the production of the annual scientific journal *Proceedings of The Royal Society of Queensland*, supplemented from time to time with Special Issues on specific themes.

Proceedings of The Royal Society of Queensland

The *Proceedings* publishes original scholarship and investigation in natural history relevant to Queensland, including the biodiversity, conservation, use, management and economic significance of natural resources. All aspects of the natural sciences, including astronomy, geology, hydrology, botany and zoology, biomedicine, introduced species and dynamic land and water processes, are considered. The journal will also publish papers on general science, including science-related history, policy, education and philosophy. Papers written from within the social sciences, such as sociology, culture and heritage that deal with the use or management of a natural resource, are welcome.

Following initial appraisal by the Editor, all submitted papers are peer reviewed by a single-blind process. The following types of manuscript are considered:

> Scientific Papers, Short Communications, Historical Reviews, Opinion Pieces, Dissertation Abstracts, Book Reviews.

Authors are required to follow the instructions given in the *Guide to Authors PRSQ 2020* which is available on the Society website or from the Honorary Editor. The timeline to allow print publication by the end of each year requires authors to submit papers to the Editor by 30 June.

From Volume 124, papers are being placed online free of charge as they emerge from the editorial and typesetting procedures. Print publication will follow when the volume is completed.

A complete archive of the *Proceedings* with full search capability back to 1884, and the preceding three volumes of the *Transactions of the Queensland Philosophical Society*, are available online.

Scholarly Debate Invited

From 2 December 2019 (Volume 124), articles accepted for the annual *Proceedings of The Royal Society of Queensland* and Special Issues have been published online with free public access. The advent of digital scientific publishing means that it also becomes practicable to publish scholarly debate over published articles. The Society welcomes critical responses to articles that have been published in this edition (Volume 128), if addressing matters of scientific substance and expressed in a scholarly manner. Please refer to the *Guide to Authors PRSQ 2020* for guidance as to style and submit all such responses the Honorary Editor. All critical responses will be subject to the review process undertaken for other submissions.

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EDITORIAL FOREWORD

The centrepiece activity of The Royal Society of Queensland is the production of the annual *Proceedings*, supplemented from time to time with Special Issues on specific themes. Whilst the year 2020 has been difficult in so many ways, it has been exceptional for the Society. Two volumes of the annual *Proceedings* and three Special Issues have been published online with free public access, as well as in print.

The present volume, PRSQ 128 2020, is divided into two main sections that serve to differentiate peer-reviewed papers from important Society reports. The first section of Volume 128 features diverse contributions from across the natural and social sciences. They include studies on forest ecology and vegetation change, the productivity and biomass of Australian rangelands, marine invertebrate and fish ecology, freshwater fish communities and river health monitoring, and historical perspectives on astronomy and tsunami hazards in Queensland. A paper on the concept of One Health and its role in the control of COVID-19 brings human health into sharp focus in a particularly timely contribution. Another paper describes plans for the recovery of Indigenous cultural knowledge through research and community activities of YACHATDAC, based in Barcaldine. Finally, a review on the legacy of the International Biological Program in Australia honours Emeritus Professor Raymond L. Specht AO, a member of the Royal Society since 1957 and a Life Member since 2015.

Royal Society reports form the second section of Volume 128. The Presidential Address "Science Through a Big Window" delivers the powerful message that "a 'business as usual' approach in scientific research will not solve our current 'big' problems, e.g. global warming, sustainable energy to drive human societies, COVID-19 and the inevitable onset of further zoonotic impacts". The Society's Annual Report (16 November 2019 to 15 November 2020) follows, with news of the continuation of activities by means of frequent Newsletters, virtual meetings and voluminous email traffic, keeping the Society in business during this extraordinary year. Reports from the Society's Research Grant program, a PhD dissertation Abstract and an Obituary honouring a dedicated scientist and teacher conclude this volume. I encourage all research students completing their degrees to take advantage of the Society's policy to publish dissertation abstracts free of charge.

I have enjoyed my year as Honorary Editor and thank the Society most sincerely for the privilege and enjoyment of working with so many enthusiastic authors and dedicated reviewers, whose insights have enriched my days and many nights throughout 2020. I have been supported at every step of the publication process by Council members, office-holders and the exceptional professional services of Darryl Nixon, Managing Director, Sunset Publishing Services Pty Ltd.

On behalf of the Royal Society, I wish all Society members and readers good health, relaxing holidays and the deep enjoyment of reading.

Angela H. Arthington
Editor, PRSQ Volume 128, 2020

The Royal Society of Queensland acknowledges the Iningai Nation, their long custodianship and inherent connection to country, its springs and waterways, plants and animals.
We pay respect to the knowledge and cultural values of First Peoples of Australia and acknowledge Elders past, present and future.

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Refereed Papers

Do Dusky Flathead, *Platycephalus fuscus* (Cuvier, 1829), Spawn in Upper Estuarine Areas?

Barry R. Pollock[1]

Abstract

This study is based on monthly samples of dusky flathead (n = 87) in the size range 40 cm TL (total length) to 75 cm TL, collected by angling methods from upper estuarine areas in southern Queensland during the spawning period (September to April). Ovaries at two stages of development were identified by macroscopic and microscopic examination: unyolked (translucent) ovaries, the most common form, in which oocytes are undergoing mass atresia up to α stage; and yolked (vitellogenic) ovaries which are also undergoing mass atresia to both α and β stages. An unusual finding is mass atresia of previtellogenic oocytes, showing multiple irregular vacuoles within the oocyte cytoplasm, which commonly occurs in both ovary types. Mature males have testes that are small and degraded. No ripe or running ripe gonads were found in the upper estuarine fish during the spawning period. It is concluded that these dusky flathead are not spawning, in contrast to the spawning aggregation fish at the Jumpinpin estuarine/oceanic interface which is 10 km to 20 km distant from the study site. Given the major differences in gonads and oocytes between spawning aggregation fish and those from upper estuarine areas, it is unlikely that mixing of the two subpopulations occurs during the spawning period. A review of size at maturity of dusky flathead estimated that L_{50} (length at which 50% of the size class has reached maturity) for females is 35 cm TL to 39 cm TL, and 30 cm TL to 34 cm TL for males.

Keywords: citizen science, degenerate gonads, oocyte atresia, size at maturity, sub-population

[1] *Sunfish Queensland Incorporated, 25 Uther Street, Carindale, QLD 4152, Australia*

Introduction

The dusky flathead (*Platycephalus fuscus*) is endemic to Australia, and its range is restricted to the east and south-east coastal regions. The species occurs throughout estuarine and coastal areas, ranging from ocean beaches, estuarine entrances to the Pacific Ocean, and estuaries to the limits of saline water (Bray, 2020). Pollock (2014) described characteristics of the annual spawning aggregation at the Jumpinpin Bar, an area where a large estuary meets the entrance to the Pacific Ocean. The present study examines gonad types and gametogenesis of adult dusky flathead which inhabit upper estuarine areas during the spawning period. The study aims to determine, by visual inspection of the gonads and by examining gonad tissues microscopically, whether this subpopulation in upper estuarine areas is capable of spawning. An understanding of the reproductive biology, including periodicity and spatial aspects of spawning aggregations, is of fundamental importance in the management of fish stocks (Morgan, 2008). In addition to the imperative to protect spawning aggregations, information on size at maturity, fecundity and parameters for population modelling is important for fishery management purposes (McPhee, 2008). Studies of the reproductive biology of wild populations of dusky flathead to date have examined populations with a focus on known spawning aggregations, spawning times and duration, oocyte development, egg quality, size and age

at maturity, and fecundity (Gray & Barnes, 2008; Hicks et al., 2015; Pollock, 2014, 2019).

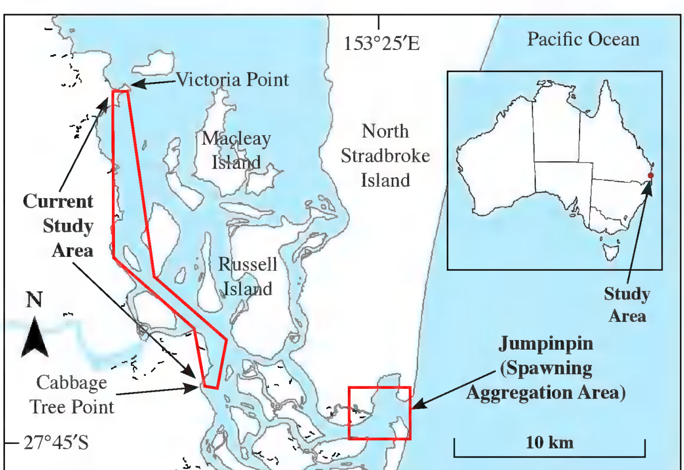
Dusky flathead have a protracted spawning period each year (austral summer, September to April), with spawning aggregations occurring at ocean/estuary interfaces (Gray & Barnes, 2008; Pollock, 2014). They are highly fecund, multiple-batch spawners, producing small planktonic eggs into oceanic waters (Taylor et al., 2020). After a short period of development and growth, the planktonic larvae settle in estuaries (Bell et al., 1987; Kingsford & Suthers, 1996), becoming benthic ambush predators (Baker & Sheaves, 1996). After settlement, dusky flathead show little latitudinal movement across different estuaries (O'Neill, 2000). The genetic study by Taylor et al. (2020) found that dusky flathead form a single stock across a large part of their distribution on the Australian east coast, where mixing most likely occurs during early life phases and through limited adult migration. Dusky flathead is not a densely schooling species. Spawning aggregations are characterised by many small associations of a single large female attended by several males. Bray (2020) provides video footage of this behaviour. Dusky flathead are rudimentary hermaphrodites with sex determined at the early juvenile stage (Pollock, 2014). Sexual dimorphism occurs with females growing to larger sizes. In the present study area, dusky flathead are most abundant at ages one year to five years, but may live to nine years (O'Neill, 2000).

Dusky flathead support popular recreational angling fisheries and commercial net fisheries throughout their range on the Australian east coast. The present study site and adjacent areas are prolific fishing grounds for dusky flathead (Webley et al., 2015; McGilvray et al., 2016). The dusky flathead fisheries are managed separately by three state fisheries agencies within their state boundaries (Queensland, New South Wales and Victoria). Routine stock assessments show that dusky flathead are currently sustainably fished (McGilvray et al., 2016). The current management arrangements for dusky flathead in all states include slot size limits (minimum and maximum size restrictions), bag or possession limits for recreational fishers, and effort controls and gear restrictions on commercial fishing. Information from the present study on the reproductive status of upper estuarine fish during the spawning period and a review of size at maturity estimates are relevant to the future management of this important species.

Materials and Methods

Monthly samples of dusky flathead were obtained by angling methods from upper estuarine areas between Cabbage Tree Point and Victoria Point (Figure 1) from September 2019 to April 2020.

Figure 1. Map showing the study area in upper estuaries and the spawning aggregation area at Jumpinpin (Pollock, 2014).



Fish in this sample (n = 101) ranged in size from 32 cm total length (TL) to 89 cm TL. Since the aim of this study was to determine the reproductive status of adult fish, those less than 40 cm TL, which are mostly immature (Pollock, 2014), were released alive without determining their sex. Three very large females exceeding 75 cm TL were also discarded to comply with Queensland fisheries regulations, requiring such fish to be released. As a result, the fish kept for detailed examination numbered 87, with a size range of 40 cm TL to 75 cm TL (Figure 2).

At capture, each retained fish was killed humanely by the participating citizen science angler in accordance with the Australian national recreational fishing code of practice (Department of Agriculture, Fisheries and Forestry, 2012). Each fish was then immediately supplied to the author for processing. Total length (TL) was recorded to the nearest 1 cm, and total weight to the nearest 5 g. Gonads were removed, photographed and weighed to the nearest 1 g. Gonad tissues, taken from the mid region of one gonad lobe, were fixed (10% neutral buffered formalin). The processed fish was then returned to the angler who caught it. A subsample of fixed tissues from 19 ovaries, including the different ovary types, and three testes were later selected for microscope slide preparations. The slides were prepared by wax embedding, microtome sectioning at 8 µm, and haematoxylin and eosin staining. The microscope slides were examined under magnifications up to 200. Gonosomatic index (GSI) was calculated for each fish (gonad weight/total body weight 100). All ovaries and testes were staged according to the criteria given in Table 1.

Figure 2. Size frequency and sex of all dusky flathead collected from upper estuarine areas during the spawning period, September 2019 to April 2020 (n = 101).

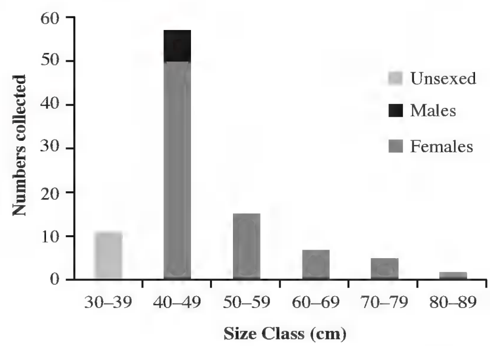


Table 1. Ovarian and testicular developmental stages of adult dusky flathead (*Platycephalus fuscus*) collected from upper estuarine areas during the spawning period. Modified from Bani et al. (2009) and Poortenaar et al. (2001).

Gonad type	Macroscopic appearance	Microscopic details
Unyolked (translucent) ovary	Ovary clear almost transparent. Colour variation from colourless, pale yellow, or red (Figure 3).	Small previtellogenic oocytes, most being degenerate with multiple large vacuoles in the oocyte cytoplasm (early mass oocyte atresia). Atresia to α stage in some oocytes showing disintegration of the nucleus and zona radiata, with only the follicle remaining in advanced stages (Figure 4).
Yolked (vitellogenic) ovary	Ovary yolky and larger than unyolked ovary. Yellow to red in colour. Vitellogenic oocytes observed through the ovary wall (Figure 5).	Previtellogenic and vitellogenic oocytes present, many being degenerate (mass atresia). Previtellogenic oocytes, same as for unyolked (translucent) ovary, with multiple large vacuoles in the oocyte cytoplasm, and others at α stage atresia. β stage atresia common in vitellogenic oocytes, composed of disorganised granulosa cells surrounded by a thin thecal layer (Figure 6).
Testes	Testes small in comparison to spawning aggregation males. Degenerate but producing small amounts of white seminal fluid when dissected (Figure 7).	Spermatozoa present at all stages of development.

Figure 3. Unyolked (translucent) ovaries of dusky flathead from upper estuarine areas showing colour variations: (A) Colourless translucent ovary of specimen collected in April, 61 cm TL; (B) Yellow translucent ovary of specimen collected in September, 54 cm TL; (C) Red translucent ovary of specimen collected in November, 74 cm TL.

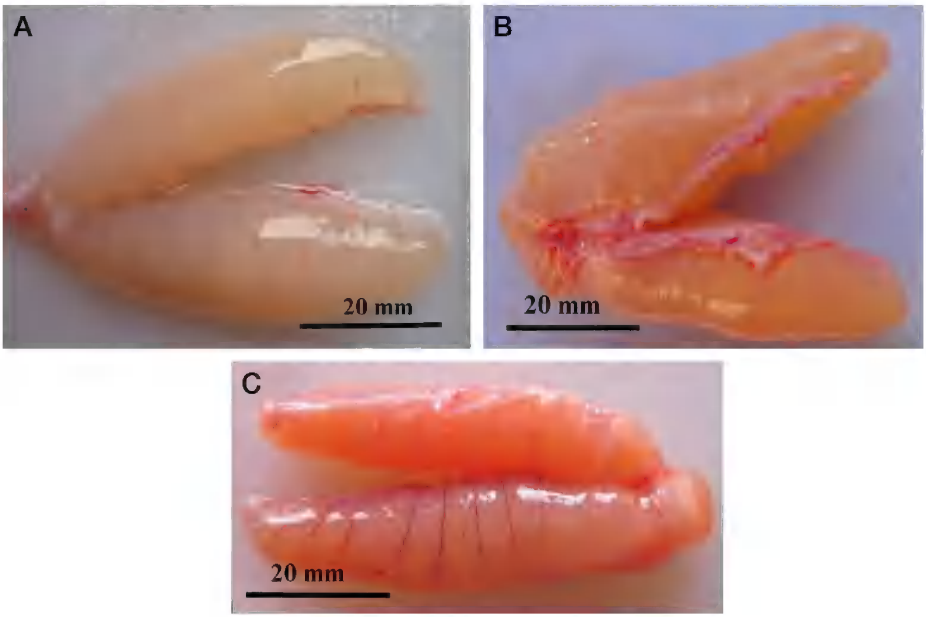


Figure 4. Microphotographs of unyolked (translucent) ovaries of dusky flathead taken from upper estuarine areas showing mass oocyte atresia: (A) Specimen collected in March, 65 cm TL; (B) Specimen collected in January, 75 cm TL. V – previtellogenic oocyte with numerous vacuoles in oocyte cytoplasm. αA – α atretic oocyte.

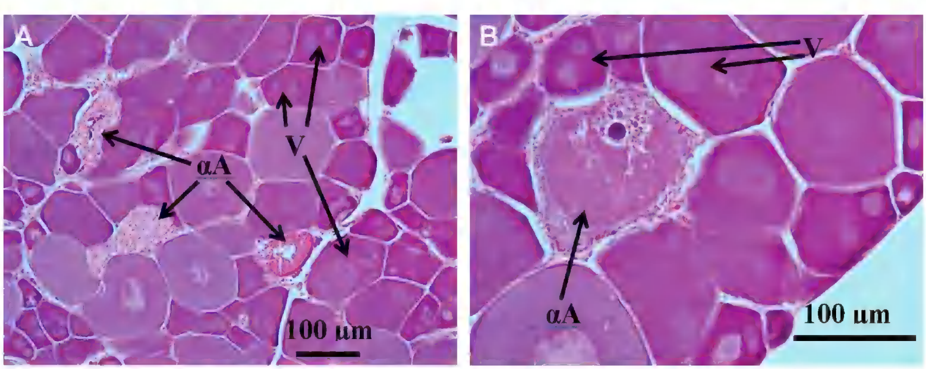


Figure 5. Yolked (vitellogenic) ovary of a dusky flathead taken from the upper estuarine area in November, 54 cm TL. Vitellogenic oocytes are visible through ovary wall.

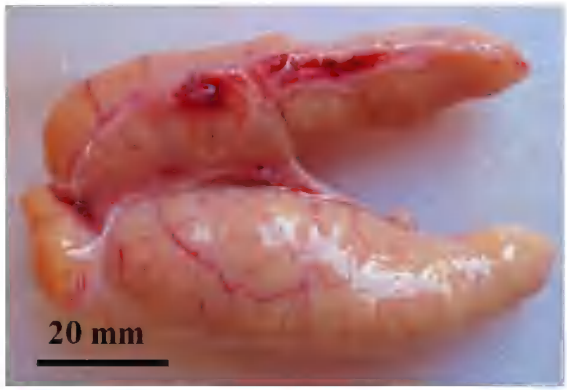


Figure 6. Microphotographs of yolked (vitellogenic) ovaries of dusky flathead taken from upper estuarine areas showing mass oocyte atresia: (A) Specimen collected in April, 69 cm TL; (B) Specimen collected in November, 74 cm TL. VO – vitellogenic oocyte. V – previtellogenic oocyte with numerous vacuoles in oocyte cytoplasm. αA – α atretic oocyte. βA – β atretic oocyte.

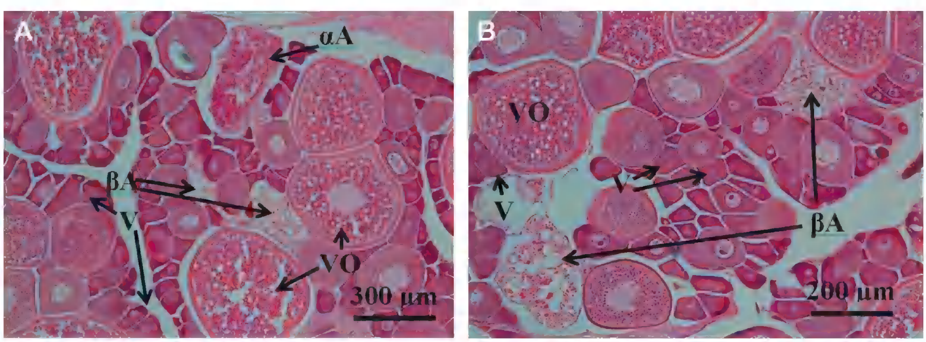


Figure 7. Testis of a dusky flathead which is small and degenerate. Specimen collected from upper estuarine area in December 2019, 41 cm TL.

Results

The sample of dusky flathead for detailed examination was dominated by female fish (females = 80, males = 7; Figure 8). The sampling period was from September to April and corresponded with the annual spawning period in southern Queensland. Male fish were relatively small (40 cm TL to 49 cm TL). Female fish were present in all size classes (40 cm TL to 75 cm TL), but more common in the smaller sizes (Figure 8). Staging of gonads showed all males possessed degenerate testes. Male GSI was small throughout the sample (GSI = 0.52 ± 0.06. Mean ± 1SE, $n = 7$). Small amounts of white seminal fluid were released during dissections of testes from the fish. Staging of ovaries (Figure 8) established that the unyolked (translucent) type was numerically dominant and occurred in all size classes, including the large size classes, 55 cm TL to 75 cm TL. Yolked (vitellogenic) ovaries were less common but also occurred in all size classes except for the 55 cm TL to 59 cm TL group, which is most likely due to the small sample size. Mean GSI values for females were relatively low throughout the spawning period (Figure 9). In September–October, GSI variability was greatest, indicating variations in ovary size during early development at the commencement of the spawning period. Mean GSI for females from November to April ranged from 1.0 to 1.4, and GSI showed less variability during this period (Figure 9), indicating less variation in ovary development later in the spawning period.

Figure 8. Ovarian stages of size classes of dusky flathead taken from upper estuarine areas during the spawning period, September 2019 to April 2020 ($n = 80$).

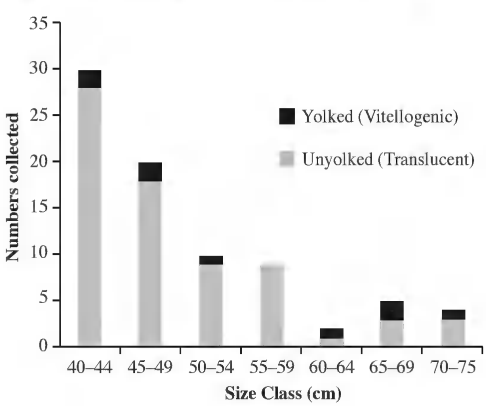
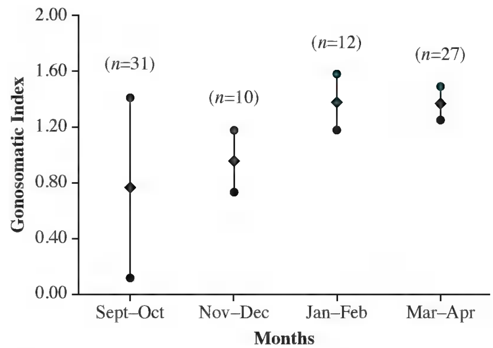
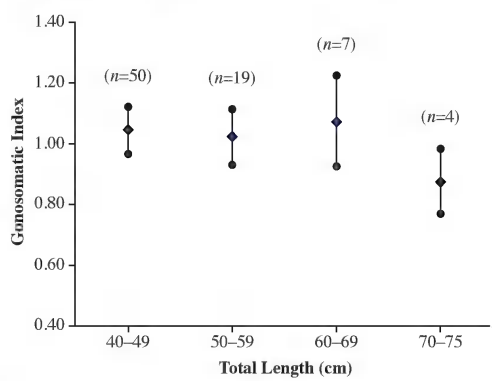


Figure 9. Bimonthly gonosomatic index values (mean ± 1SE) of female dusky flathead taken from upper estuarine areas during the spawning period, September 2019 to April 2020.



Mean GSI values for females were relatively stable with little variability across size classes (Figure 10), which is an indication of similar levels of ovarian development in females of different size classes.

Figure 10. Gonosomatic index values (mean ± 1SE) of size classes of female dusky flathead taken from upper estuarine areas during the spawning period, September 2019 to April 2020.



Microscopic examinations of oocytes revealed similarities and differences in the two ovarian stages. The unyolked (translucent) ovaries were dominated by previtellogenic oocytes at an early stage of mass oocyte atresia, namely multiple irregular vacuoles in the oocyte cytoplasm (Figure 4). Also present, but less common, were α atretic oocytes. The yolked (vitellogenic) ovaries had previtellogenic oocytes at

the early stage of atresia (multiple large vacuoles), and α atretic oocytes, similar to unyolked (translucent) ovaries. However, vitellogenic oocytes were also common, many at β stage atresia. Mass oocyte atresia was also occurring in all yolked (vitellogenic) ovaries. Macroscopic and microscopic examinations of the ovaries from upper estuarine female dusky flathead revealed that ripe and running ripe individuals were absent during the spawning period (September to April).

Discussion

Sampling Methodology and Study Area Characteristics

In the present study dusky flathead were obtained from upper estuarine areas by citizen science recreational fishers, using hook-and-line angling methods. The author was present at all times during the collection of samples, enabling data to be obtained from recently caught fish, quality photographs to be taken of fresh gonads from all retained fish, and fixation of good-quality tissue biopsies of gonads for subsequent histological processing. The author was also able to ensure that all dusky flathead were treated humanely when released alive or when killing was necessary.

The study location for collection of dusky flathead within upper estuarine areas is 10 km to 20 km distant from the closest spawning aggregation site, the Jumpinpin estuary/oceanic interface (Figure 1). Water quality characteristics vary considerably between the two sites. Most notably, turbidity is higher, and temperature and salinity are more variable in the upper estuarine sites (Blaber & Blaber, 1980; Abal & Dennison, 1996). The present study location is also influenced by summer rain events and is occasionally subject to flooding. The larval stages of dusky flathead are sensitive to water quality, especially salinity (Pham et al., 1998).

Gonad Staging of Dusky Flathead from Upper Estuarine Areas

Male dusky flathead in the upper estuarine areas during the spawning period are all mature, releasing seminal fluid from freshly dissected testes. However, the testes are small and degenerate with very low GSI values (GSI = 0.52 ± 0.06. Mean ± 1SE). Given the poor condition of testes of males from the upper estuarine areas, it is unlikely that they are capable of spawning during the reproductive period. In comparison, spawning aggregation males have large testes in good condition (Figure 11) and much higher GSI values with monthly means ranging from 1.5 to 1.9 (Pollock, 2014). The sex ratio of dusky flathead in upper estuarine areas during the spawning period is dominated by females (11.4 to 1). Within the Jumpinpin spawning aggregation during the spawning period, the proportion of females to males is approximately equal (Pollock, 2014). This is an indication that the males are more likely to participate in spawning aggregations.

Figure 11. Testis from a running ripe male dusky flathead collected in the study by Pollock (2014) from the spawning aggregation at the Jumpinpin estuarine/oceanic interface in January, 44 cm TL.

Ovaries at two stages of development are present in female fish of all size classes in the upper estuarine areas during the spawning period: unyolked (translucent) ovaries and yolked (vitellogenic) ovaries. In both ovary types, mass oocyte atresia is occurring. The common occurrence of atresia in previtellogenic oocytes, with large irregular vacuoles in the oocyte cytoplasm and fewer α atretic oocytes, is unusual (Figure 4). There are few reports of previtellogenic oocyte atresia in other species of fish, showing multiple irregular vacuoles within the oocytes (Miranda et al., 1999). Oocyte atresia commonly commences at the vitellogenic oocyte stage in other species of fish (Roe Hunter & Macewicz, 1985; Lubers et al., 2010). Mass oocyte atresia was not observed in spawning aggregation dusky flathead smaller than 70 cm TL (Pollock, 2014). However, degenerate ovaries with mass oocyte atresia are present in approximately half of the very large females examined in spawning aggregations at estuarine/oceanic interface areas during the spawning period (Pollock, 2014, 2019). Mean bimonthly GSI values for upper estuarine female

dusky flathead during the spawning period ranged from 0.9 to 1.4 (Figure 9). In comparison, mean monthly values of GSI for spawning aggregation females are much higher, 3.3 to 4.5 (Pollock, 2014). Mass oocyte atresia has been reported in many wild populations of fish (Rideout et al., 2005) and is attributed mainly to poor nutrition (Rideout & Tomkeiwicz, 2011).

Ovaries of immature dusky flathead within spawning aggregation sites are unyolked (translucent). Microscopic examination of these immature ovaries shows that previtellogenic oocytes are present in good condition (Pollock, 2014, 2019). These immature dusky flathead have clear oocyte cytoplasm, lacking multiple vacuoles which commonly occur in previtellogenic oocytes of the two ovarian stages of upper estuarine fish. In addition, oocyte atresia is rare in immature dusky flathead at the spawning aggregation sites (Pollock, 2019). It was not possible to distinguish immature from mature dusky flathead females with previtellogenic (translucent) ovaries taken in upper estuarine areas in the present study. At the Jumpinpin spawning aggregation area, immature dusky flathead of both sexes are present in low frequencies during the spawning period. The proportion of immature females is approximately 10% of all females in the 40 cm TL to 50 cm TL size classes at the spawning aggregation area (Pollock, 2014). In these size classes at Jumpinpin, mature females dominate abundance. It is expected that immature females may also be present in small numbers at upper estuarine areas during the spawning period in the size class range 40 cm TL to 50 cm TL. This size class contains females from ages 1+ to 5+ (Gray & Barnes, 2008), and therefore this size class in upper estuarine areas is expected to contain mature females which skipped their first spawning and mature females that had spawned in previous years, as well as a small proportion of immature females.

O'Neill (2000) staged dusky flathead gonads in samples taken 100 km to 300 km to the north of the present study site, with the aim of determining reproductive status throughout the year. The resulting stages for adult female dusky flathead, based on macroscopic examination alone, were limited to two categories: Stage 2 (resting/recovering), which matches the unyolked (translucent) ovary classification in the present study, and Stage 3 (developing) which matches the yolked (vitellogenic) ovary classification of the present study. No ripe or running ripe dusky flathead, indicative of estuarine entrance spawning aggregation fish, were reported in that study. The results obtained by O'Neill (2000) for ovary stages are similar to the findings of the present study, indicating that samples in that study were obtained from upper estuarine areas.

Spawning Strategies

The present study shows that female dusky flathead in upper estuarine areas are not spawning in those areas during the spawning period. Non-spawning mature dusky flathead in poor reproductive condition, both males and females, in upper estuarine areas may provide a reservoir of potential spawners in subsequent years as condition and energy reserves improve. This reproductive strategy, involving a large subpopulation of mature fish not participating in an annual spawning aggregation, occurs in other teleost species. Examples of this from the Australian east coast are yellowfin bream (*Acanthopagrus australis*) (Pollock, 1984) and sea mullet (*Mugil cephalus*) (Stewart et al., 2017).

The spawning of dusky flathead close to oceanic waters at the entrance to estuaries in preference to upper estuarine areas is most likely an adaptation to ensure maximum survival and dispersal of the early life stages. Several other teleost fish of importance to fisheries on the Australian east coast have similar reproductive strategies. Examples are the yellowfin bream (*Acanthopagrus australis*), tailor (*Pomatomus saltatrix*) and sea mullet (*Mugil cephalus*) which all have seasonal spawning aggregations at coastal oceanic locations or at the estuarine/oceanic interface, planktonic early life stages in oceanic waters, and postlarval settlement in inshore waters, estuaries or streams, dependent on the strategy of the particular species (Pollock et al., 1983; Zeller et al., 1996; Stewart et al., 2017).

Subpopulation Mixing of Upper Estuarine Fish with Estuarine/Oceanic Interface Spawners

The degree of mixing of the subpopulation of dusky flathead from upper estuarine areas with the subpopulation from the estuarine entrance spawning aggregation was not directly investigated in the present study. Tagging studies of dusky flathead within estuaries (O'Neill, 2000; Gray & Barnes,

2015) found that of the fish recaptured, more than 90% were taken in the same estuary. However, in these studies, information on the sex of the recaptured fish and details of movements within the estuary were not recorded. Within an annual spawning period, mixing of the two subpopulations is unlikely, based on the major differences in gonad morphology and oocyte differences established in this study and Pollock (2014). In the case of males, the degenerate testes of upper estuarine fish would need to undergo rapid development to achieve the condition of testes of the spawning aggregation fish during the annual spawning period. Such a major change of the degenerate testes is unlikely. Males in the estuarine entrance spawning aggregation all have testes in good condition, and it is also unlikely that males in this subpopulation would undergo rapid testicular degeneration and move to upper estuarine areas in a given spawning period.

In the case of female dusky flathead, a change from small ovaries with mass oocyte atresia associated with the upper estuarine areas to reproductive condition of ovaries of spawning aggregation fish (ripe and running ripe) within a given spawning period again seems unlikely. Similarly, change in the advanced ovaries of spawning aggregation fish to small degenerate ovaries with mass oocyte atresia within a given spawning period is not expected. Mixing of the two subpopulations from one spawning period to the next has also not been determined but is expected to occur. The strategy in dusky flathead of having part of the adult population as a discrete spawning subpopulation at an estuarine/oceanic interface and another subpopulation in non-spawning condition in alternative feeding grounds in the upper estuarine areas in a given year is possibly an adaptive mechanism. This adaptation could act to balance reproductive output and adult population survival in a species which has several potential spawning age classes.

The present study has examined adult dusky flathead in the upper estuarine areas which are 10 km to 20 km from the nearest spawning aggregation site. Marked differences in gonad and oocyte condition have been identified when comparing fish from the two different sites. A topic for further research is the reproductive status of dusky flathead between the two extremes – between the upper estuaries and the estuarine/oceanic interface spawning aggregation sites. An understanding of mixing and boundaries between the two subpopulations over time would be an important addition to understanding the reproductive biology of this species.

Size at Maturity Estimates for Dusky Flathead – An Update

Information on size at maturity is important for fishery management purposes. It is often used to determine minimum sizes or lower slot limits, as well as being a parameter for population modelling. It is also important in estimating fecundity. There are several ways to estimate size at maturity, but a common method is to determine the size at which a given proportion of the population reaches maturity (Tripple & Harvey, 1991). Gray & Barnes (2008) estimated the mean length at maturity (L_{50}), the length at which half of the population is mature, for male (32 cm TL) and female (57 cm TL) dusky flathead in New South Wales. Hicks et al. (2015) determined L_{50} for female dusky flathead in Victoria (33 cm TL) and noted the large difference in comparison to the Gray & Barnes (2008) estimate. The L_{50} estimate by Gray & Barnes (2008) uses Stage I (ovaries appear as small clear threads) and Stage II (ovaries appear as clear lobes) to determine immature female dusky flathead during the spawning period. The sample in that study included dusky flathead from all areas, including fish from upper estuarine areas as well as those close to spawning aggregation sites. Gonad staging was carried out without microscopic examinations to determine the developmental stage of oocytes. The use of macroscopic examination to stage gonads with either no complementary microscopic comparisons or limited microscopic examination can lead to errors in gonad staging (West, 1990). Female dusky flathead classified as immature (Stage II with clear lobed ovaries) by Gray & Barnes (2008) are expected to include mature non-spawning females from upper estuarine areas. The result is that a large proportion of mature female fish, which dominate the unyolked (translucent) stage in upper estuarine areas, were excluded from the calculation of L_{50} because they were classified as immature by Gray & Barnes (2008). The present study shows that mature females with unyolked (translucent) ovaries occur in all size classes but are most com-

mon in smaller size classes (Figure 8). The estimate of female size at maturity of 57 cm would be lower if mature females in the upper estuarine areas were correctly staged. The calculation of L_{50} for female dusky flathead in the present study was not possible because immature and mature females could not be separated, both possessing unyolked (translucent) ovaries. L_{50} for spawning aggregation fish was not determined in the previous study (Pollock, 2014). However, from the graph of length–frequency of mature male and female dusky flathead within the spawning aggregation in Pollock (2014), abundance of mature fish peaks at 35 cm TL to 39 cm TL for males and 40 cm TL to 49 cm TL for females. L_{50} is expected to occur in slightly smaller size classes in comparison to the peak abundance of mature fish. Therefore, based on qualitative examination of Figure 3 in Pollock (2014), an approximation of 30 cm to 34 cm TL for males and 35 cm to 39 cm TL for females is estimated for L_{50}. This L_{50} value for females is similar to the estimate by Hicks et al. (2015) of 33 cm TL, but much smaller than that by Gray & Barnes (2008) of 57 cm TL. In the subsequent paper, Gray & Barnes (2015) added details of a microscopic examination of ovaries, but information on the source of the tissue samples and a thorough examination detailing macroscopic and microscopic features of all gonad types are not provided. Gonad staging results given in the subsequent paper (Gray & Barnes, 2015) are identical to those given without microscopic examination (Gray & Barnes, 2008). In the case of male dusky flathead, mature fish in the upper estuarine areas can be identified by the macroscopic examination of testes because these males have small white (degenerate) testes (Figure 7). The estimates of L_{50} for male fish are similar in the two studies: 32 cm TL (Gray & Barnes, 2008), compared to 30 cm TL to 34 cm TL (Pollock, 2014).

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Author Profile

Barry Pollock is the voluntary Scientific Officer of Sunfish, a peak body for recreational fishing in Queensland advocating responsible fishing practices and sustainable fish stocks. He was raised at Redcliffe on the shores of Moreton Bay. After high school he was awarded an undergraduate Commonwealth scholarship to attend The University of Queensland, and has degrees to doctorate level in zoology and fisheries science. He held senior positions in fisheries agencies: Deputy Director, Pacific Islands Forum Fisheries Agency (2000–2004); General Manager, Fisheries Resource Management; and Director, Fisheries Branch, Queensland Department of Primary Industries (1989–2000). His research interests are Queensland's coastal finfish fisheries. Since retirement he has been appointed to several Queensland Government fisheries advisory bodies.

Population Structure of *Canarium labiatum* (Röding, 1798) (Mollusca: Neostromboidae: Strombidae) on Green Island, Great Barrier Reef, Queensland

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Abstract

Canarium labiatum is a small gastropod of the Strombidae family that is commonly encountered in the inter-tidal zones of tropical Queensland, Australia, yet little is known of its population structure. A targeted survey of the *Canarium labiatum* population on Green Island, located near Cairns, Queensland, was conducted on 12 August 2015. Ninety adult specimens were collected, of which 49 were female and 41 were male. The sample demonstrated significant sexual axial-length size dimorphism, with a bias towards larger females. While we collected more females than males, this did not represent a statistically significant bias, and rather may reflect the clustering nature of the sample. In addition, there was no evidence of pseudohermaphroditism in females within the population under consideration. Interestingly, 11.1% of the sample did not show banding and brown/grey-blue maculations on a light grey shell, the typical colour pattern associated with *Canarium labiatum*. This paper fills a knowledge gap in Queensland's *Canarium labiatum* population structure and provides a basis for a wider study into the size dynamics of Strombidae in general, but *Canarium* in particular.

Keywords: *Canarium labiatum*, clustering, colour, imposex, pseudohermaphroditism, sex bias, size dimorphism

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Introduction

Strombidae Rafinesque, 1815 is a frequently encountered marine gastropod family common to most tropical oceans. Members of the Strombidae express sexually dimorphic characteristics in both physiology and shell morphometrics, particularly in relation to the mean body size and length of the adult shell (Abbott, 1949, 1960, 1961; Reed, 1993a; Mutlu, 2004). The shells of individuals within a population may vary greatly, with occasional examples having rare colour phenotypes (Abbott, 1960). Some species, such as *Strombus pugilis* Linné, 1758 (Reed, 1993b) have demonstrated that there are more than two sexes within a population, with the reporting of masculinised females, a condition referred to as pseudohermaphroditism, or imposex, and defined

as the imposition of male sexual characteristics on females in gastropods (Jenner, 1979; Nicolaus & Barry, 2015). There is little or no knowledge regarding any of these population characteristics in members of the stromboid genus *Canarium* Schumacher, 1817, worldwide, with most work having been conducted during the mid to late twentieth century on taxonomy and basic physiology (Abbott, 1949, 1960, 1961; Geary & Allmon, 1990; Reed, 1993a).

Evidence from fossil beds and large collections of extant taxa indicate that sexual axial-length size dimorphism in Strombidae is a pleisiomorphic state, with a strong bias towards larger females (Geary & Allmon, 1990). Strombidae vary greatly in the mean size of adults within a population, and in the expression of sexual dimorphic characteristics in both physiology and shell morphometrics (Abbott, 1949, 1960, 1961; Reed, 1993a; Mutlu, 2004; Arularasan et al., 2011). However, it is necessary to explore the phenomenon of sexual dimorphism in novel taxa within the wider Neostromboidae (Maxwell et al., 2019) to establish the extent of this phylogenetic constant within the wider clade. Greater understanding of the phenomena of sexual size dimorphism will inform on the evolutionary limitations of size divergence.

The extent of pseudohermaphroditism expression in Queensland's Strombidae is another area that has not been explored. In Strombidae, pseudohermaphroditism is often associated with the superimposition of a penis onto females (Reed, 1993b; Cardenas et al., 2005). The presence of pseudohermaphroditism has varying effects on taxa, ranging from sexual impotence to no physiological effect on reproductive biology (Vlasconcelos et al., 2006). In masculinised female *Strombus pugilis*, the size of the dysfunctional external male sexual organ ranges from 2–12 mm, with no difference in ovarian structure between masculinised and normal females (Reed, 1993a). The presence of this penile gland in *Strombus pugilis* has no effect on the sexual function of the masculinised female as it is located on the edge of the egg groove (Reed, 1993b). Males and normal females are smaller than masculinised females when considering both size and shell to body mass ratios (Reed, 1993b; Cardenas et al., 2005). For example, in *Conomurex luhuanus* (Linné, 1758) populations, shell size of males was larger than normal females, but lighter in mass compared to masculinised females, which were larger in all size traits (Reed, 1995). However, Reed (1993b) found no evidence for this state in *Lobatus costatus* (Gmelin, 1791) after the examination of 500 specimens, suggesting an absence of masculinised females. Interestingly, there is no information on the presence of pseudohermaphroditism in *Canarium*.

Another population dynamic that has remain unexplored in many Strombidae is the occurrence of colour morphs. Rare colour phenotypic expression is well documented in the Strombidae (Kreipl et al., 1999). However, the relative abundance of these colour forms within a population has not been fully explored in many species. While some species are famous for their variability, such as *Canarium urceus* (Linné, 1758) which can be found in all colours of the rainbow and blends of those primaries (Abbott, 1960), other species have limited phylotypic plasticity in colouration. For example, *Canarium klineorum* Abbott, 1960 changes in shade and depth of colour, but there is limited variability in the base colour of this taxon. The level of colour variation within many *Canarium* populations in Queensland is not yet known.

One such overlooked species, *Canarium labiatum* (Röding, 1798), is a gregarious and locally common species across its known range of the Central Indo- and Eastern Pacific with typical banding and brown/grey-blue maculations (Abbott, 1960). This species has a high tolerance for environmental variability, such as temperature, indicated by the extent of its range from the equatorial shallow waters past the 30° latitudes (Abbott, 1960). It is also found in a diverse range of habitats, from coral outer reefs (Sudbury Cay, Queensland) to near-coastal muddy rocky reefs (Yule Point, Queensland).

This paper has four aims that will elucidate the knowledge gap concerning the life history and population characteristics of a discrete population sample of *Canarium labiatum* on Green Island, Queensland, Australia. The first seeks to test whether there is sexual size dimorphism in shell length. The second examines sex ratios to determine whether there is a sex-ratio bias. The third examines the expression of phenotypic plasticity in shell colouration within the sample. The fourth seeks to establish whether there is preliminary evidence of pseudohermaphroditism within the *Canarium labiatum* population under consideration.

Abbreviations

AM – Australian Museum, Sydney, New South Wales
QM – Queensland Museum, Brisbane, Queensland
QV – Queen Victoria Museum & Art Gallery, Launceston, Tasmania
SM – Collection of Stephen J. Maxwell, Cairns, Queensland

Methods

A targeted survey of a *Canarium labiatum* population located near Cairns, Queensland, Australia (16°46′S, 145°58′E) was conducted by SM on 12 August 2015. The population was identified in previous years (2013–2014) and was found to be localised and present in the general area (Maxwell & Watts, unpublished data; Figure 1). This information provided the starting point on the island from which a search for an initial *Canarium labiatum* cluster commenced. Once the first cluster ($n > 5/m^2$) was identified, the immediate area was searched using an opportunistic method, a process of searching an area until specimens were located, to determine the limits of the identified localised population to which the cluster belonged. This resulted in a 60 m^2 search area. Once the population boundary was established, all members of the population were collected within the defined area using a secondary fingertip search for four hours.

The type of clustering may affect the distribution of sex ratios between males and females. Within congregations of the same taxon, four distinct categories for clustering can be discerned: mixed age; juvenile; mating; and non-mating clusters (Brownell, 1977; Catterall & Poiner, 1983). Therefore, it is important to note the clustering nature of the sample on collection, particularly the age demographic and presence of sexual activity, as this may affect whether a sex-ratio bias is observed or not.

After collection, the total axial length of each specimen was measured. The animal was then placed on its dorsum and sexed as it righted itself: the presence of a verge indicated a male, while the presence of an oviduct indicated a female. Masculinised females are readily distinguished from males and normal females by a deformed and vestigial verge (Reed, 1995). The masculinised female verge is muscular, may be multi-lobed, and may contain superficial channels with ciliated epithelia (Reed, 1993b). During this process, we also noted the colouration of the ventral side of the shell. Atypical colouration was considered if the shell was a consistent solid colour or lacked the banded, typically brown/grey-blue maculations on a light grey shell (Abbott, 1960).

Figure 1. Green Island, showing the region of the constant presence of a *Canarium labiatum* population (Image modified from Google Earth, accessed January 2020).

Summary statistics for shell length were generated for each sex, and the means and standard errors for each sex presented to statistically demonstrate the presence of sexual dimorphism using SPLUS v2007 (Insightment Corp.). A box plot of each sex was generated to illustrate the size–frequency distributions of each sex. A pooled-variance, two-sample t-test was conducted to determine whether there were significant differences in the size of each sex. The proportion of males was tested against a hypothesised proportion of 0.5 using an exact binominal test to determine sex bias. Colour ratios were calculated as a percentage of the total sample. Pseudohermaphroditism was scored as 'present' or 'absent'.

Target Taxon

Mollusca Linné, 1758
Neostromboidae Maxwell et al., 2019
Strombidae Rafinesque, 1815
Canarium Schumacher, 1817 – Type: *Strombus urceus* Linné, 1758, p. 745, No. 440 (Maxwell et al., 2020)

Canarium labiatum (Röding, 1798)

Type: *Lambis labiata* Röding, 1798 (Martini, 1777, 3 pl. 78, Figures 804–805)

Type location: Amboina, Indonesia (Abbott, 1960, p. 68)

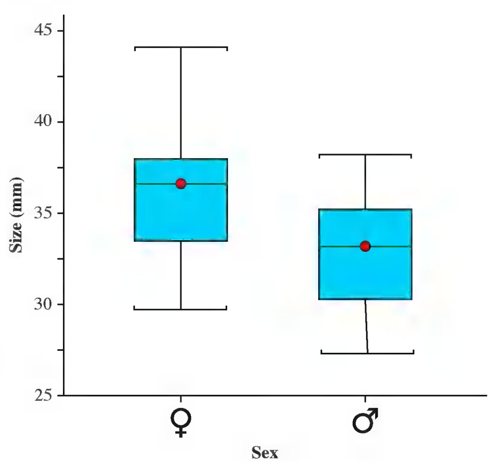
Description: The shell ranges in length from 15 to 55 mm. Solid, smooth to axially plicate, the shell has a distinctive orange columella. The columella has 25 to 40 weak, but distinct, raised lirae over its entire length, which are prominent at the ends of the columella. The outer aperture contains spiral lirae that are typically dark stained over an orange background, but in rare examples the aperture is entirely orange. The inner aperture lacks these lirations. The outer lip is well formed and thickened.

Remarks: There are seven institutional records contained within the *Atlas of Living Australia* (ALA, www.ala.org.au) for *Canarium labiatum* from Green Island, the first from 1901 to the most recent, 1978 (1901, AM – C.9665; 1929, AM – C.400361; 1961, AM – C.400152; 1969, QM – MO.83431; 1973, QM – DM.11576062; 1975, AM – C.400362; 1978, QV – QVM.9.9932). At present, no literary records for the occurrence of this species on Green Island are known to the authors.

Results

The sample of *Canarium labiatum* contained primarily adults (96.8 %; total $n = 90$; female $n = 49$; male $n = 41$), with no evidence of copulation, indicating a non-mating cluster. The sample suggested an average population density of 1.5/m^2 within the study perimeter. Three sub-adults and three dead specimens were observed within the search area but were excluded from further analysis as their sex could not be determined. The mean size of females was 35.91 mm (± 0.45 SE), in contrast to males, which had a mean size of 32.81 mm (± 0.46 SE). This difference in size, biased towards larger females, was statistically significant ($t_{2,88}$ = 4.79, $p < 0.001$). The size distribution of each sex indicates that females have a wider size distribution range than males (Figure 2).

Figure 2. Boxplots of the axial lengths of each sex of *Canarium labiatum* within the study population on Green Island.



The number of males collected was smaller than the number of females (1:1.19), although this difference was not statistically significant ($p = 0.46$; $\alpha = 0.95$). While most (88.9%) of the sample exhibited typical colouration of maculation in greys and greens, 11.1% showed atypical colouration, with five yellow-shelled specimens (5.6%), four chocolate-coloured specimens (4.4%), and one coffee-coloured

specimen (1.1%; Figure 3), recognised by the colour of the ventral side *in situ* (Figure 4). Of the 90 specimens collected, there was no evidence of pseudohermaphroditism.

Figure 3. Colour forms of *Canarium labiatum* observed within the study population on Green Island: (A) typical maculated (37.5 mm, female, SM 23.043ag); (B) typical banded (37.0 mm, female, SM 23.043h); and the more uncommon (C) coffee (31.5 mm, male, SMC 25.070q); (D) yellow (34.5 mm, female, SM 23.043m); and (E) chocolate (44.5 mm, female, SM 23.043i) forms.

Discussion

This study confirms the presence of sexual axial-length size dimorphism in a non-mating, primarily adult aggregation of *Canarium labiatum* on Green Island, Queensland. The distribution of female sizes was broader than males, with the distributions of both sexes overlapping. This makes the assessment of the sex of a shell based on size problematic, a pattern that is not uncommon in this group of molluscs, given several examples of stromboid size-dimorphic distributions in both extant and extinct taxa (Geary and Allmon, 1990; Reed, 1993a). However, while female size may overlap male size significantly, males tend to occupy only the lower half of the size distribution in the sample studied. Therefore, selecting the largest members of a sample adult population, irrespective of clustering type, will result in a biased selection towards females. The study population showed a non-significant bias towards females over males. The different clustering possibilities have implications for the determination of sex bias towards more females and, thus, can be problematic to statistically establish from a single sample (Abbott, 1949; Wiedemeyer, 1998; Mutlu, 2004; Maxwell et al., 2017).

This study found that 11.1% of all specimens showed an atypical colour pattern to the typical bands and maculations. This is the first time that the colour proportions within a population of *Canarium labiatum* have been reported. This historical lack of knowledge on colour ratios is problematic, given the propensity of recreational collectors and

Figure 4. *Canarium labiatum* observed within the study population on Green Island: (A) Ventral views of living yellow and coffee colour forms; (B) Dorsal view of a yellow sub-adult *in situ* (Image: U. Weinreich, 12 August 2015).

commercial fishermen to frequently target rarer and more aesthetically pleasing specimens because of the higher price they command, with typical phenotypes not being collected. As such, knowing the colour proportions within a population has implications for understanding the potential impact of selective harvesting on the entire population.

That no pseudohermaphroditism was found indicates one of three possibilities:

1. The presence of TBT (tributyltin) and its derivative compounds are not present at concentrations high enough to affect the population. TBT is a marine pollutant commonly known to cause pseudohermaphroditism, and may reflect the distance to sources of TBT (Vlasconcelos et al., 2006; Amiard & Amiard-Triquet, 2015).
2. The sample size was too small to observe this rare characteristic (Reed, 1993b).
3. This phenotype is simply not naturally present in this population.

We suggest that further studies are required, such as testing the water quality of this region and surveying other *Canarium labiatum* populations to establish the reason for the lack of pseudohermaphroditism.

Conclusion

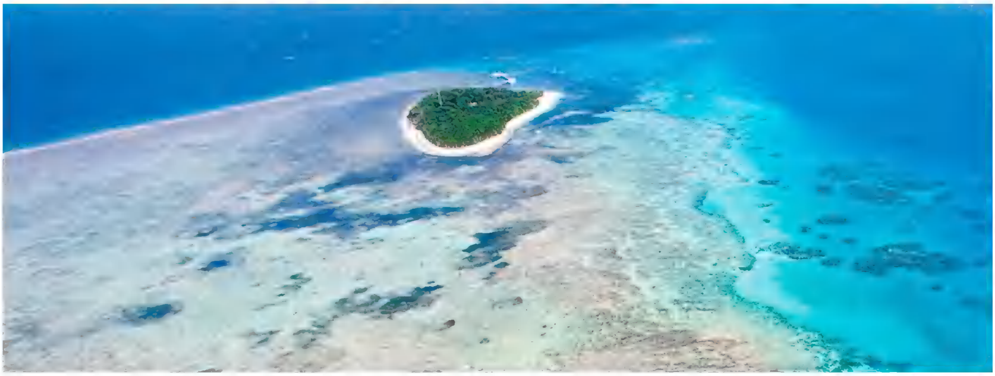
In the current study, female *Canarium labiatum* were larger than males and more abundant. The colour and pattern variability of most of the population was typical, with greenish maculations, with only a limited number (11.1%) of atypically coloured phenotypes observed. We found no evidence for pseudohermaphroditism in females. *Canarium labiatum* offers researchers an opportunity to explore with ease many of the life history traits of Strombidae due to its accessible intertidal habitat and abundance. This study fills a knowledge gap in overlooked members of the Strombidae and an opportunity to establish the extent of sexual axial-length size dimorphism and sex bias within the wider clade, as well as the potential for these population traits to have an impact on size evolution within the Strombidae.

Acknowledgements

This research was conducted under Marine Parks and GBRMA Permit No. G15/37503.1.

Green Island is a small (12 ha) coral cay formed on the sheltered side of a platform reef. It became part of the Great Barrier Reef World Heritage Area in 1981 (Source: https://greatbarrierreef.org/islands/green-island/).

The island and reef are part of the traditional sea country of the Guru-Gulu Gungandji Aboriginal people, who know the island as *Wunyami*. Today the Guru-Gulu Gungandji people retain a strong spiritual connection with their country and are active in managing the island.



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Tasmin Rymer is an animal behaviourist at James Cook University (Cairns). Her research primarily focuses on proximate questions of animal behaviour, specifically the ontogeny of, and mechanisms underlying, parental care behaviours, personality and cognition. Tasmin's research spans across multiple taxa, including arthropods, molluscs and mammals.

Gracevale, a Case Study on Caring for Country and Rediscovery of Culture and Language by the Iningai People in Central West Queensland

Sharon M. Brown[1,2], and Suzanne Thompson[1]

Abstract

Much Indigenous culture has been lost as a result of colonisation, and the current Iningai generation do not speak their language and know little of their history. The Yumbangku Aboriginal Cultural Heritage and Tourism Development Aboriginal Corporation (YACHATDAC) based in Barcaldine has been formed by key members of the Traditional custodian families of the Iningai lands in Central West Queensland. The board is composed of 80% Aboriginal and 20% non-Aboriginal members. Gracevale is an 8870 ha property in Central West Queensland owned by YACHATDAC. It will become a sustainable place of education and centre of excellence based on consensus around resolution of reconciliation and teaching, and an important example of Indigenous management in the conservation and extension of culture and best-practice land management in the arid zone of Australia under a changing climate. YACHATDAC is working to rediscover language and the cultural significance of local rock art and ceremonial sites; developing sustainable land-use practices using traditional methods, along with science and technology, to restore degraded land, natural springs and waterways; enhance above- and below-ground biodiversity; and create native fauna reserves. Income streams to support sustainable management of the system are being developed. They include: responsible grazing practice; cultural and eco-tourism; a seed bank and commercialisation of native seeds and plants; and use of Gracevale as a living sustainable laboratory for the development and dissemination of knowledge about natural ecosystem functions and processes and the monetisation of ecosystem services.

Keywords: Indigenous culture, education, land restoration, income streams, cultural and eco-tourism

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Introduction

The Iningai people were one of the largest Aboriginal tribes in Central West Queensland. Their territory includes 50,500 square kilometres: west of the dividing range to Longreach, and north to Aramac and Muttaburra. Language, knowledge, song, spirit, ceremonial practice and Country are inseparable for Aboriginal Australians, and they believe that culture must be held for future generations and that Indigenous cultural knowledge should be respected alongside Western knowledge and education.

Much Indigenous culture has been lost as a result of colonisation, and the current Iningai generation do not speak the language and know little of their history. The Yumbangku Aboriginal Cultural Heritage and Tourism Development Aboriginal Corporation (YACHATDAC), based in Barcaldine, has been formed by key members of the Traditional custodian families of the Iningai

lands in Central West Queensland. The board is composed of 80% Aboriginal and 20% non-Aboriginal members. Starting with Gracevale, YACHATDAC has begun to restore their traditional Country while at the same time preserving and strengthening culture.

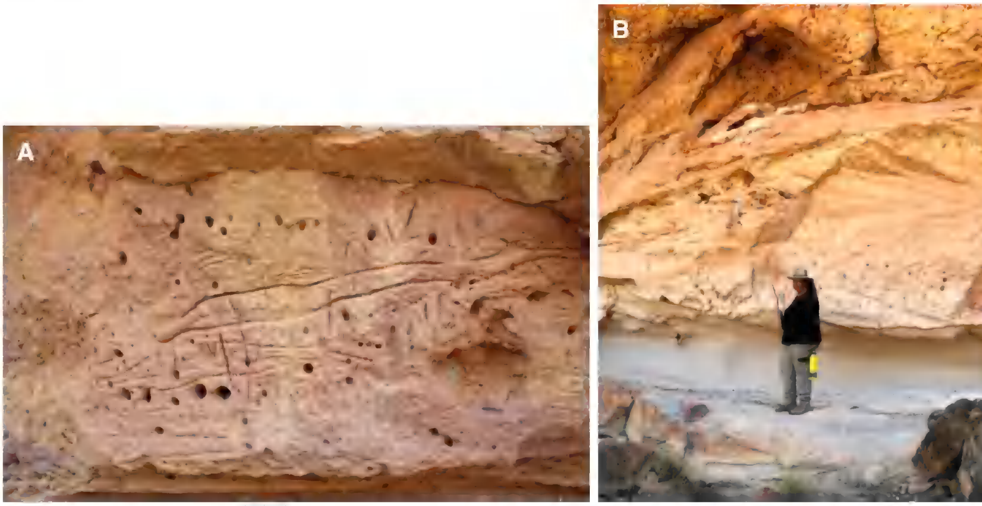
Gracevale

In 2019, ownership of Gracevale Station was returned to members of the Iningai people through YACHATDAC. Gracevale Station, with an area of 8870 hectares, is located 120 km north of Barcaldine in Central West Queensland. The site is contained within the Desert Uplands (DEU) bioregion and is characterised by upland landforms dominated by sandstone ranges and deep, infertile sandplains. Gracevale is positioned on the eastern margins of the Great Artesian Basin (GAB) and is an important recharge area for the aquifers of the GAB. The semiarid climate with variable rainfall is generally vegetated with open eucalypt and acacia woodlands, and an understory of spinifex, natural grasses or acacia (Figure 1).

Historically, Gracevale has been used for cattle grazing. Much of the pre-existing vegetation has been cleared to facilitate pasture growth. Introduced grasses, invasive weeds and pest species such as cane toads, feral cats and wild pigs, along with overgrazing by stock, tree clearing and fire, have altered the natural ecology of the area. Seven culturally significant artesian springs have been modified for water extraction for homestead and stock use. Two of these springs are now dry, and waterways have been eroded.

Figure 1. A natural spring, one of seven that YACHATDAC is restoring (top left); trees dead due to drought (top right); caterpillars feeding on new foliage following rain (bottom left); and spinifex flowering after rain (bottom right).

Figure 2. (A) Ancient rock art. Is this a *Pliosaurus* in the desert? This is one of the questions being studied by archaeologists. (B) Suzanne Thompson at a unique site that describes the Seven Sisters songlines, among the most significant of the creation tracks that crisscross Australia.



Gracevale incorporates a unique set of caves on the edge of the Aramac Range, containing rare examples of traditional Aboriginal rock art that have not been studied (Figure 2). Within 10 km of Gracevale, an escarpment with a labyrinth of weathered caves and blowholes was the site of the massacre of forty Aborigines in 1869 by Government Troopers. To date, the cultural heritage and history of the Iningai people has not been formally recorded or studied. The restoration and preservation of Gracevale Station and the local area is the first major project undertaken by YACHATDAC.

Managing for Sustainability

The property is to be managed so that it becomes environmentally and economically sustainable, and this will be achieved through multiple income streams including: cattle grazing; cultural and eco-tourism; development of a seed bank and commercialisation of native seeds and plants; and use of Gracevale as a living laboratory for the development and dissemination of knowledge about natural ecosystem functions and processes, sustainable management and the monetisation of ecosystems services. YACHATDAC will partner with the Land Regeneration Group (https://www.landregenerationgroup.com/) to implement a project approved for funding under the Restore Program. Activities will support the goals of caring for Country while increasing carbon sequestration above and below ground. The Indigenous Land and Sea Corporation (ILSC) supported YACHATDAC in securing a Land Restoration Fund agreement that provides revenue of $725,000 over five years.

These endeavours call for a multi-dimensional, integrated research approach with three key elements:

1. Understanding spiritual connection to land.
2. Caring for Country.
3. Economic development.

Research Approach and Priorities

YACHATDAC has formed a strong collaborative network and seeks partners and funding to assist in the following priority areas.

Understanding Spiritual Connection to Land – Conserve and Understand the Rock Art of Gracevale

Example activities and research ideas include:

- Develop a database to collate oral/written histories and archaeology results.
- Survey and record rock art, surface artefacts

and natural springs for the region; add to a database.

- Excavate key places; determine a minimum age for the engravings and paintings; and explore ancient activity areas/pathways/Dreaming trackways.
- Prepare a management plan to conserve and manage the rock art for the benefit of future generations:
  (a) Use the oral history and archaeological information, regional patterns (e.g. activity areas/pathways) and conservation issues.
  (b) Detail how best to manage sites, cultural tourism initiatives and promotion through a website, schools, conferences and academic publications.
  (c) Develop traditional songlines described in the rock art with assistance from an Indigenous astronomer.

Caring for Country – Restoration of a Landscape Degraded by Sheep and Cattle Production

Example activities and research ideas include:

- **Soil.** Landscape restoration initiatives will take a ground-up approach starting with soil improvement. Design best-practice grazing management to help to build organic carbon and soil quality. Restoring soil health will help mitigate the effects of climate change; increasing organic matter in soil enhances its ability to hold water; improving soil structure allows more rainfall to infiltrate into the ground, better sustains grass and crops during droughts, and helps reduce flooding downstream.
- **Water.** Restore the waterways and springs as close as possible to their original state and therefore improve biodiversity, correct salinity and create landscapes more resilient to drought, floods and bushfires.
- **Reforestation.** Reforest and recover the landscape using appropriate shrub and tree species, and thus contribute to carbon sequestration and improve biodiversity.
- **Biodiversity.** Develop diverse and complex vegetation systems to help create habitat and corridors for endangered wildlife and nationally listed threatened species.
- **Climate change.** Predict how a changing climate will impact on water, reforestation, soil and biodiversity in order to design best-practice land management; develop a carbon-neutral beef production enterprise.
- **Natural capital market.** Seek to gain benefit from carbon sequestration in soil, vegetation and biodiversity conservation, engaging carbon project developers to assist in becoming market ready to tap into the environmental services market.
- **Society.** Facilitate evidence-based discussion of fundamental natural processes and functions, including through sponsoring citizen science, to assist land managers in making improved decisions and to enable monitoring of the leading performance indicators.

Economic Development – Benefits of Landscape Restoration for Landholders, Community and the Nation

Example activities/research ideas include:

- **Cultural tourism.** Engage with archaeologists to describe the cultural sites on Gracevale and use this as an evidence base for conservation and tourism development.
- **Economic development of native foods.** Engage scientists and commercial companies to select, grow and multiply native species with high commercial potential.
- **Natural learning laboratory for education and storytelling.** Develop Gracevale as a centre of excellence for training and learning, with a focus on sustainable land management practice and local cultural history to support Reconciliation and Consensus building activities.
- **Planning tool.** Using the research outputs from land restoration, develop a planning tool for the roll-out of future landscape restoration projects. The tool could measure and demonstrate:
  (a) a return on investment for landholders;
  (b) the value of ecosystem services provided for greater community; and
  (c) the value of natural capital restored/created for Australia.

Summary

YACHATDAC has made remarkable progress and achieved all goals set by funders in record time. An excellent strategic plan has been developed for Gracevale, with support from The University of Queensland. YACHATDAC plans to become a Centre of Excellence for training and knowledge sharing and has already established infrastructure that allows hosting of training camps at Gracevale. Strong research networks have been developed, providing an opportunity for the development of holistic solutions for land regeneration that can be used widely through Australia.

YACHATDAC calls for people interested in contributing to the development of Gracevale and engaging in the development of collaborative research projects. There is also a strong need for wages to support jobs needed to continue to develop the property as an Indigenous owned and managed cultural, training, research and tourism hub.

Acknowledgements

YACHATDAC acknowledges support from Indigenous and non-Indigenous volunteers and advisors who have visited Gracevale and undertaken research needed to provide the basis for future activities. These include The University of Queensland, University of New England, Australian National University and Birdlife South Queensland. Particular thanks go to Gerry Turpin who established the Tropical Indigenous Ethnobotany Centre, in partnership with James Cook University; Victor Steffensen, advisor on fire-stick burning and author of the book *Fire Country*; Vincent Forrester, Aboriginal elder who assisted in interpreting the stories on rock art at Gracevale; and Sheena Gillman, Chair of the Birdlife South Queensland Conservation Subcommittee.

Author Profiles

Sharon Brown is an award-winning scientist with over 20 years' experience working in close collaboration with researchers, businesses and landholders to reverse land degradation in Australia and South East Asia. She is a Senior Research Fellow in the School of Agriculture and Food Science, University of Queensland, Head of Research and Project Development for YACHATDAC, and Director of Research and Development with the Land Regeneration Group.

Suzanne Thompson is Managing Director at YACHATDAC (Yambangku Aboriginal Cultural Heritage and Tourism Development Aboriginal Corporation), and Chair of Native Foods and Botanicals, She has a strong and varied background in management and as a cultural educator, community development practitioner, youth development traditional performer, artist, business owner, trainer/facilitator, conference MC and events coordinator.

On a Fine Day in Shorncliffe the Sea Came Boiling Upwards Across the Bathers ...

Colin Lynam[1]

Abstract

Australia's historical scientific archives are open for investigation by citizen scientists, such as myself. They hold our unique primary scientific records, data and references, and they are found in universities, museums, state libraries and government agencies, national archives and on researchers' PCs. While our paper archives have recently been exposed to digitisation, modern digital scientific information is not being upgraded and collated into our modern digital knowledge-management 'data mining' global computational systems. I am writing this awareness article, flavoured with 40 years of seismological engagement and as a purposeful contribution in support of World Digital Preservation Day (22 November 2020), 'At Risk Digital Materials'. This paper establishes that Queensland has an incomplete 'public' history of local tsunami hazard occurrence. Further, it announces the discovery of a new meteotsunami meteorological hazard occurrence on 3 June 1917. By retrieving the various types of archived data, this paper questions and reflects on our society's lack of tsunami hazard preparedness, highlighting an obvious decline in scientific rigour in communicating such knowledge about our environment. This discussion of meteotsunamis illustrates the multivariate complexity of weather systems, with climate-change-related phenomena capable of creating coastal tsunami-like hazards commonly causally linked to undersea earthquakes and/or landslip or tectonic fault movement.

Keywords: tsunami hazard, meteotsunami, tsunamigenic, earthquake, archival preservation, FAIR data re-use

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Introduction

Is it really possible for suburban Brisbane, Australia, to feel the damaging inundation effects of tsunami sea waves from a local, tsunamigenic earthquake, as suggested by the title of this paper? How likely is it that a devastating tsunami, generated by a large earthquake off the shores of South America, or even caused by a local weather event, could occur here? Most of Australia's population lives along the coastal and littoral waterways, like those of the Gold Coast (Figure 1) and Sydney Harbour. How much inundation can we tolerate?

Surely our government agencies, charged with our safety, would have considered this? Unfortunately, they have not. The simple, underlying reason is that objective scientific knowledge is not a valued, integral part of government strategy. There is a paucity of measurement data research on this topic, and this paper suggests the ways in which this came about.

The latest Queensland Government advice from the Minister for Emergency Services (Hon. Craig Crawford) is documented in the *Tsunami Guide for Queensland*:

> We realise, since a hazard such as a tsunami has not impacted Queensland in recent memory, that this does not mean that it cannot happen. Tsunami are rare, highly directional events. Because our historical records are short, and damaging tsunami are relatively rare in this region, there are large uncertainties in how

often they might occur in Queensland. Further, scientists still do not have a good understanding of the frequency of key tsunami generating processes such as large earthquakes and volcanic eruptions (Chesnais et al., 2019).

The Queensland Government's publication mentions only the effect of the 1960 Chilean earthquake tsunami. Nor does the Minister announce a strategy for the scientific research needed to correct the paucity of knowledge in his purview for this natural hazard. It is within his brief to fund necessary research to fill this identified and acknowledged lack of scientific knowledge. Interestingly, the statistics from the Queensland State Disaster Council for 2018–2019 (Tot & Pringle, 2019) issued regular 'Weather Warning' alerts for:

- 80 tsunamis;
- 194 tropical cyclones;
- 84 storm tides;
- 88 high seas/ocean winds; and
- 943 severe thunderstorms.

All of these weather-related phenomena (see Glossary) affect sensors for tide gauges, barometers, pluviographs or seismographs and are visible in those record repositories, as well as various satellite sensor platforms.

A recent Engineers Australia (EA) seminar expounded on how a cavalier society deals with this resulting lack of factual knowledge:

> Hundreds of thousands of Queenslanders live on coastal floodplains, often unwittingly until they are actually flooded. In the past 10 years floods in South East Queensland, Bundaberg and Townsville as well as elsewhere have brought into question urban planning decisions, building designs, emergency planning and flood mitigation strategies. Yet there continues to be pressure to put more dwellings in floodplains, often replacing existing development with higher density development (Mirfenderesk et al., 2020; Bavas, 2019).

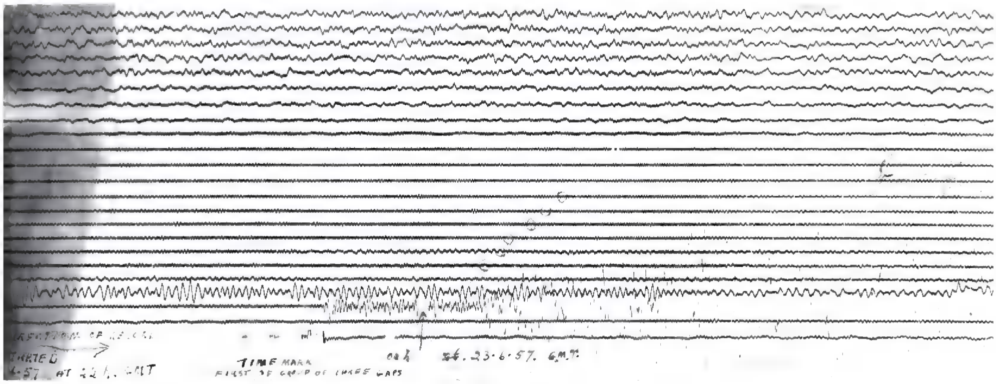
I draw attention here to seismologists, who also have worked actively in this area of science. I have noted elsewhere in regard to Figure 2 that:

> I came across the 1957 correspondence and 2 seismograms from the late Father Joe McKey from St Mary's Church in Warwick. One of these seismograms appears below and shows how well the 1957 Magnitude 7.1 BIAK (Indonesia) earthquake was captured on Fr. McKey's home built 'Milne Shaw' seismograph. The other interesting recorded phenomenon to note is the enlarged microseismic background noise at the top of the seismogram, for which Father McKey's research is recognised. This was a Tropical low moving SE from inland NSW, strong high in Tasman Sea, strong NEE gradient. Complex lows formed near coast (Lynam, 2018).

Seismograms record earthquakes and microseism background earth noise, due to ocean weather such as tropical cyclones and lows. The University of Queensland was tracking cyclones back in 1954 on its seismograms, before the advent of radar in meteorology (Upton, 1956).

Figure 1. Gold Coast, Queensland – highly built-up coastal and littoral floodplain susceptible to tsunami or storm surge inundation.

Figure 2. Annotated 1957 seismogram from 'Milne Shaw' seismograph built by Fr. Joe McKey, showing M 7.1 Biak region, Indonesia, 22 June 1957, at 23:50:35 UTC, and (upper record) noise effects from a low-pressure weather system from EW polarity.



Evidentiary Material (Part 1)

This paper presents a sequence of some known tsunami events affecting Queensland, to demonstrate that these are very real and hazardous threats. Let me illustrate my contention with some recently uncovered instances of tsunami events in South East Queensland. These events are not widely known by seismologists, the Australian tsunami research community, or government.

I have deliberately represented my 'specimen' evidence with a graphical format, because I am writing this manuscript in a digital medium, but the primary evidence is in an analogue (newspaper) referenced format. If it were a botanical or geological specimen, it would be presented as an inset photograph. Instead, for the reader's convenience, I have used the scanned, 'secondary source' information provided by the Trove newspaper scanning project of the Australian National Library.

Tsunami Event, 7 June 1918 (Earthquake mb5.6, Offshore Fraser Island, Queensland)

This anecdotal digitised newspaper clip extracted from the newspaper *The Daily Standard* refers to an observed tsunami caused by an offshore Queensland earthquake, mb5.6, at 4.15 am (AEST) on 7 June 1918. It is Queensland's largest historically and scientifically documented earthquake (no local seismographs). There is a further anecdotal record of this same tsunami, 400 km further north and offshore from Mackay.

The Daily Standard, 7 June 1918, p. 5 (Anon., 1918a):

> "Sandgate and Redcliffe residents report that quite a severe shock was felt in that region, and that the disturbance was so great as to create something of a tidal wave, the extent of which may be gauged from the fact that the sea washed right across the picture show enclosure at the head of the Sandgate jetty" (see Figure 3 below).

The Townsville Daily Bulletin, 11 June 1918, p. 4 (Anon., 1918b):

> "The schooner Clyde arrived in port on Saturday afternoon in charge of Captain Romer. When off Flat Top early on Friday morning, the Clyde encountered a tremendous swell, which was probably caused by the earth tremors which were experienced at Mackay, and further south on Friday morning [Flat Top Island 21.162°S 149.246°E (5 km E of Mackay)]."

The earthquake epicentre was located offshore of Queensland, approximately north-east of Fraser Island and east of Heron Island. The Richter magnitude ~mb5.6 earthquake, generated a very wide swathe of felt effects across Central and South East Queensland. A survey of the public's felt effects from this earthquake was conducted soon

afterwards by Dr W. H. Bryan and Professor H. C. Richards from the former Department of Geology at The University of Queensland (Hedley, 1925). These original paper records are located in The University of Queensland Seismograph Stations Collections (now defunct). The nearest seismograph recording of this tremor was at Riverview Jesuit Observatory, Sydney, 1000 km to the south of Brisbane.

Unfortunately, all the tide gauge records for this same date in 1918 from the Pile Light pilot station (Brisbane River) are missing from their Queensland State Archives repository. I assume that the charts were borrowed and never returned: "I looked at the contents of B/3131 that covers 1910–1919 and there are no items dated in 1918 – your reference that all for 1918 were sent to British Admiralty may be right" (G. Dobeli, Queensland State Archives, pers. comm., 27 November 2017).

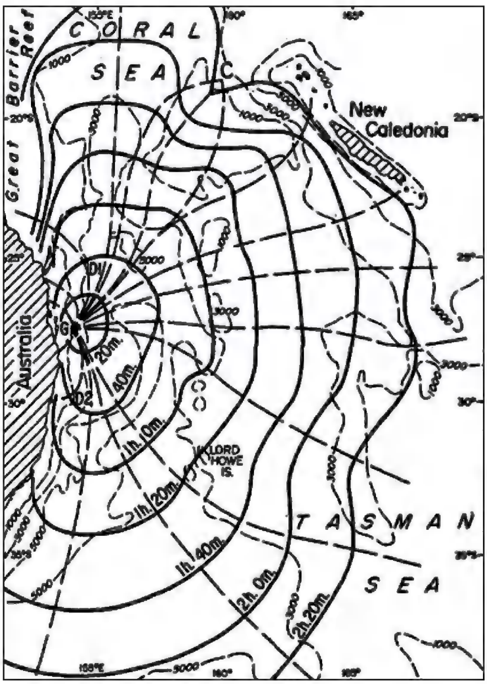
In the early 1970s, high-grade programmable (Hewlett-Packard) calculators became common instead of the standard mechanical Friden electric calculators, closely followed by larger university computer systems. Predictive approximation of tsunami travel times over ocean pathways were part of that era of transforming scientific methodology. Roger Braddock (Griffith University) was an early researcher in the newly evolving hazard discipline of tsunami prediction and warning systems (Braddock et al., 1981, 1994; NOAA, 2017). One of his models (Figure 4) illustrates how little warning time there exists for the Brisbane public to flee to higher ground (if an alarm were raised) when the next near-offshore Queensland tsunamigenic earthquake occurs.

Exemplified in this paper are the multidisciplinary backgrounds of the science researchers and the hazard managers. The tsunamis being discussed in this paper have various causes, ranging from underwater land slips triggered by earthquakes which resulted from shifting tectonic plates, to slumping of massive sedimentary accretions on continental slopes or meteorological super-cell weather events.

Early Australian tsunami research was directed by the late Dr Tad Murty (1937–2018), National Tidal Facility at Flinders University (Braddock et al., 2001). After the Aceh (Indonesia) catastrophic tsunamigenic earthquake of 2004, this facility transferred operations to the Bureau of Meteorology (BoM) Australian Tsunami Alert System (ATAS) facility (ca 2008). Currently, the Joint Australian Tsunami Warning Centre (JATWC) is operated by the Bureau of Meteorology and Geoscience Australia (GA).

Figure 3. Bathing area, Shorncliffe, Queensland, ca 1910. Photo taken from pier looking towards Moora Park. Seats on the right-hand side are for patrons attending 'Open Air Pictures' event (Photo courtesy of Redcliffe Historical Society).

Figure 4. The tsunami travel time chart for Brisbane. The hypothetical epicentre (G) is located at 27.5°S and 154°E. Only the 1000 m, 3000 m and 5000 m bathymetric contours are shown on the chart, and the wave fronts are spaced at 20-minute intervals. Divergent zones are indicated by D1 and D2, and C indicates the location of the caustic (Source: Rynn, 1994).



Before establishing JATWC, BoM published a preparatory Australian tsunami statistics paper (Rynn & Davidson, 1999), and the seismologist author noted "false-tsunami": "These include meteorological effects (such as hurricanes, cyclones, east coast lows and Southern Ocean Lows and tidal effects (such as tidal bores)."

In Queensland, recent research (Clarke et al., 2019; Rigby, 2017; Mollison et al., 2020) reveals evidence of massive seafloor slumping along our coast in the geological past. It can happen again:

> Submarine landslides are present in water depths of approximately 400 to 3500 m along the entire length of continental margin, but are increasingly prevalent northward of Coffs Harbour without clustering at any particular water depth. Two hundred sixty individual submarine landslide scars that are greater than 1 km in width have been identified. Of these, 36 have been calculated to produce a tsunami flow depth equal to or greater than 5 m at the coastline for an assumed landslide downslope velocity of 20 ms^{-1}. Landslides that are both thick (> 100 m) and wide (> 5 km) have the greatest potential to generate the largest coastal flow depths of (> 10 m) (Clarke et al., 2019).

Tsunami Event, 27 August 1883 (Krakatoa Volcano Explosion, Indonesia)

Further investigation reveals that this phenomenon is not an unusual event. In a publication of The Royal Historical Society of Queensland, titled *Chronicles of Coochiemudlo* (Jones, 1993), we read of an August 1883 Moreton Bay (Qld) tsunami reportedly associated with the devastating explosion of the Krakatoa volcano in Indonesia on 27 August 1883. The tsunami waves had radiated around the oceans of the world:

> "During the last week of August 1883, a cataclysmic event hit the island. What was described as a wall of water like a chalk mountain, surges down the Bay, flooding low lying contiguous areas as it swept towards Innes Island at great speed. Four men were washed overboard from a southern bound boat and were lost from view. On the western side of the island the wave tore through the mangroves before smashing into the cliff. On the eastern side the (Murwong) Beach bore the full force of the wave as it crashed through the casuarinas, and continued on its way to the southward, ripping off branches, snapping trunks, uprooting trees and leaving a trail of destruction.
>
> "When the inundation had drained away, the island resembled a battlefield, with debris strewn all along (Norfolk) Beach and out into Moreton Bay."

Other tsunami waves have been recorded on tide gauges along Australia's east coast and documented in newspapers. Some were triggered by

large tsunamigenic earthquakes occurring as far distant as South American tectonic subduction plates. Such occurrences have actually caused minor damage in Australian ports. The coincidence of the arrival of a tsunami with a king tide is definitely a future disaster waiting to happen.

Sydney: "The Gauge is fixed at Fort Dennison the tidal wave of the harbour marked on the diagram made its appearance at 5:20 am on the 11th of May, 1887 and the oscillations gradually increased to a maximum of 42 inches [1.067 m] and on the 13th they gradually died away.

"Note: The 'Boomerang' steamer was being taken on the A.S.N & Co slip at noon when one of the waves came in and lifted her suddenly off the cradle, and then receding, left her high and dry."

Brisbane: "Several tidal disturbances have been observed in Moreton Bay. No gauge there for information."s

Other tsunami events noted for Sydney: On 20 August 1868: "Greatest oscillation (crest to hollow) of 34 inches [0.864 m] and 25-minute interval between waves."

Another on 15–17 August 1878: "Greatest oscillation 31 inches [0.787 m] with average intervals of 25 minutes."

(Josephson, 1878)

Tsunami Event, 11–13 May 1877 (M_w9 Iquique Earthquake, Chile)

The Fort Dennison Tide Gauge (11 May 1877) distinctively presents the tsunami's effect on Sydney Harbour (Figure 5). This tsunami chart was preserved in a scientific journal and illustrates the ongoing tsunami disturbance amplitude overlaying the daily high and low tide gauge measurements. It is compared to the gauge at Newcastle (Josephson, 1878).

Tsunami Event, 22 May 1960 (Mw9.5 1960 Valdivia earthquake, Chile)

Extract from Tsunami 94 Workshop, Brisbane, 25 August 1994:

"On May 22nd 1960, the ML8.3 Richter Magnitude earthquake from offshore Chile generated a radiating tsunami across the Pacific Ocean, travelling at 350 km / hr and reached the Australian coastline 17,000 km away some 17 hours later.

"**Brisbane** – Boats moved from moorings in Cabbage Tree Creek, Shorncliffe. A 24-inch rise in sea level measured at the Pile Light gauge showing 16 rises over a 12-hour period.

"**Evans Head** – 3 trawlers ran aground in freak waves.

"**Newcastle** – Trawler sank. 8 launches ripped from moorings in Throsby Creek.

"**Sydney** – Overturned several launches. Smashed barge into Spit Bridge. Set moored logs adrift in Balmain shipyards and swept them down Parramatta river. Swept away beach Clontarf Reserve Point Par. Exposed submarine cable.

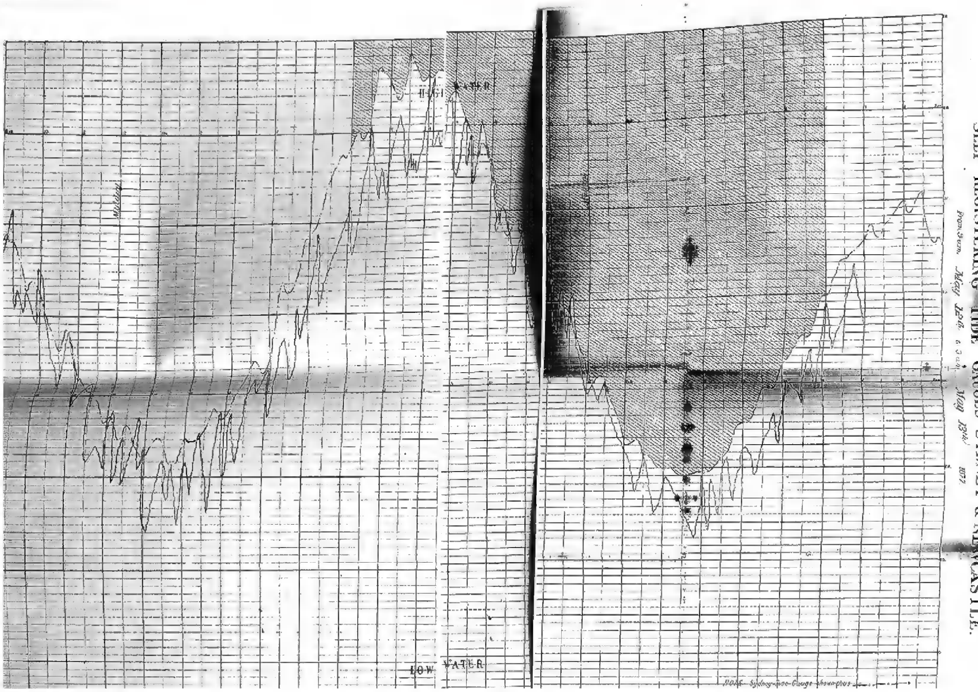
"**Wilson's Promontory** – Large waves disturbed coastal areas."

(Rynn, 1994)

Readers may be surprised by tsunamis' speed: ~1000 km/h over deep (~5 km) ocean paths. Here I quote some pertinent points about tsunamis from Geoscience Australia's fact sheet (Geoscience Australia, 2020):

- Tsunamis can travel at speeds up to 950 km/h in deep water, which is equivalent to the speed of a passenger jet.
- Several significant tsunamis have impacted Australia's north-west coast region. The largest runup resulted from the 2006 Java tsunami that was recorded at 7.9 m AHD at Steep Point, Western Australia. The largest reported offshore wave height was 6 m near Cape Leveque from the August 1977 Sunday tsunami.
- The tsunami that reached the Australia coast at Steep Point on 17 July 2006 was generated by a magnitude 7.7 earthquake south of Java. The tsunami caused widespread erosion of roads and sand dunes, extensive vegetation damage and destroyed several campsites up to 200 metres inland (Geoscience Australia, 2020; Pelinovsky, 1997; Gregson & Van Reeken, 1997).

Figure 5. Effects from tsunami (11 May 1887) at tide gauges for Fort Dennison (Sydney) and Newcastle.



Evidentiary Material (Part 2)

Meteorological Tsunami (Meteotsunami) in South East Queensland – A Proposed New Typology of Weather-related Hazard

Archival evidence is presented of another form of tsunami with a weather-related causal driver (not seismic) – the 'meteotsunami' – whose occurrence has been classified using a recently published climate hazard typology. Climate change researchers (Zscheischler et al., 2020) have identified this type of climatic hazard in their new typology of compound weather systems, as 'multivariate events', which are defined by the co-occurrence of multiple climate drivers and/or hazards in the same geographic region, causing a societal impact (Table 1). These meteotsunami events will be classified according to the researchers' extreme-event typology. It will hopefully mesh the climatology research on 'east coast lows' with more tide gauge data analysis.

Table 1. Proposed climate event typology of the meteotsunami (Zscheischler et al., 2020).

Event	Modulator	Associated weather systems	Precondition	Climatic drivers	Hazard(s)	Potential impact
Compound precipitation and wind extremes	—	Tropical and extra-tropical cyclones, severe storms	—	NSW 'east coast low'	Heavy precipitation, extreme winds, coastal erosion, meteotsunami	Infrastructure

Only a few meteotsunamis have previously been described in Australia. They are reported in synoptic weather reports, newspaper archives and tide gauge reports in South East Queensland and Western Australia. The impact is felt as a sudden sequence of ocean waves with the climatic driver(s) causing a sudden onset of larger wave height near to the shore. Meteotsunamis are likely to sweep rock fisherman into the sea or cause rapid coastal erosion. For example, on 14 August 2014, port facility damage was reported in Freemantle (Western Australia):

> Strong currents generated by the Meteotsunami resulted in a ship being moved away from the quay and breaking the mooring bollard, which in turn released the next ship upstream which broke its mooring lines, moved upstream and struck a railway bridge which sustained severe damage (Metters, 2019; Pattiaratchi &Wijeratne, 2014).

The east coastal Australian meteotsunamis are caused by an intense low-pressure trough or micro-cyclonic or 'super cell' weather feature, explosively moving over large near-shore water. This associated weather system phenomenon is also known to meteorologists as an 'east coast low' (ECL) (Bureau of Meteorology, 2007; Rynn et al., 1999). It is similar to the intense weather mechanism that gives rise to water spouts or tornadoes. The phenomenon begins as wind-shear gravity air-pressure waves that abruptly induce a significant volume of water displacement, and this energy manifests as a deep long-wave period of 10 to 15 minutes, with a wave sequence of some 10–20 distinct waves travelling inshore and heightening as the sea floor shallows. These events are increasingly important because their hazard and their instance will be likely to increase with climate change extremes and threaten marine infrastructure (Pattiaratchi, 2016). In July 2020 we watched two such ECLs rapidly develop off the New South Wales coastline and cause coastal erosion.

The regular occurrence of these events (2–3 events per annum at any given location) in Western Australia involves a large spatial area – for example, a single system can influence water levels over a region of several hundred kilometres as the intense thunderstorm travels along the coast. In Queensland, this weather feature was observed by the State Coastal Management Branch:

> The Gold Coast, with its low tidal range, has a relatively increased vulnerability to storm tide inundation compared with, for example, Mackay, where the tidal range is quite high. Significant non-cyclonic weather events such as monsoonal surges or deep extra-tropical systems are capable of producing smaller but often more prolonged increases in coastal water levels. The available Gold Coast analyses include an allowance for easterly trough low weather systems, based on the climatological analyses in McMonagle (1981) where the northern New South Wales coastline was examined in some detail. Future studies may consider the effect that low impact but higher frequency events might have on the overall statistics of water level variation (Harper, 1998).

Occurrence of these meteotsunami events around Australia is barely known, as no coordinated analysis between weather observers or tidal record observers has been undertaken routinely. These wave energy packets scour the shallow estuaries and then crash their engorged mass onto the shore, with wave runups of 10–100 m above the high tide mark (HAT) (highest astronomical tide). The waves scour and carry sediment and expose buried wrecks. Their suddenness is a hazard to the public and infrastructure.

A New Instance of Meteotsunami on 6 June 1917 (Causal Trigger: Local 'Super Cell' Weather System)

The Brisbane Courier, Friday, 8 June 1917, p. 6 (Anon., 1917b):

> "OCEAN PHENOMENON.
> "SUDDEN MOUNTAINOUS SEAS IN CALM WEATHER.
> "BOATING PARTIES' SENSATIONAL EXPERIENCE.
>
> "An ocean phenomenon occurred on Wednesday night. At dusk the sea was quite calm along the south-eastern coast, but at 6 o'clock, without any apparent reason, the air being comparatively still, a heavy swell suddenly

set in, and by midnight great breakers were rolling in heavily on the beaches. The state of the sea was officially recorded as "4." The booming of the mountainous breakers on Moreton and Stradbroke Islands was so plainly heard in Wynnum and Manly, 17 to 20 miles away, that the sleep of a number of residents was disturbed and yesterday the roar of the surf was more plainly heard than has been the case for many years. At the time the sea suddenly rose six motor boats were anchored off the Yellow Patch. They were the Gee Whiz and Wynnum (owned by Mr. Crouch of Wynnum), Ethel (manned by Arthur Ackworth and Joseph Clett), Rewa (owned by Mr. W. Crouch of Bulimba), and two sharpies (belonging to Messrs. Lihou Bros., of Sandgate). The Ethel's engines broke down, and the Rewa and the two sharpies attempted to tow her away from the shore, but were not successful. As they were in danger themselves, they were forced to leave the Ethel, and battled against the heavy sea until they reached Bribie Passage in the early hours of yesterday morning. The Wynnum was washed ashore at Yellow Patch and smashed, but the Ethel managed to reach Cowan-Cowan. The crews of all the boats were landed safely. A dinghy belonging to the Rewa, with a net, was lost, but as there is a boat lying upside down at Yellow Patch it is thought to be the dinghy. The boat, which was completely wrecked, was 30ft. in length, with an 8 hp engine, and was valued at about £300. She was not insured. The sea was so heavy that the pilot steamer Matthew Flinders was unable to return from the North-West Channel to the Cape, and took shelter at Caloundra. The cause of the sudden agitation of the sea can, of course, only be surmised at present. It may have been due to the tropical disturbance that has been in existence off the Queensland coast for several days, or to a tidal wave caused by some submarine upheaval."

I have located the Brisbane tide gauge chart for 6 June 1917 in the Queensland State Archives, but the copy of its traces is seriously faded and not interpretable (Queensland State Archives Series ID 16939, Tidal Records, 2020). Instead, I will utilise physical observation data (Table 2) to summarise and compare it with the known documented South East Queensland meteotsunami of 3–4 December 2016, which was detected on 34 tide gauges in South East Queensland (Metters, 2019; Anon., 2017). By this comparative process, I hope to reasonably justify and record this new meteotsunami occurrence, in the absence of a related tide gauge record.

The evidence for this new meteotsunami is derived from two newspaper clips. One is from *The Brisbane Courier*, "Ocean Phenomenon", above, which gives a detailed observational account of several fishermen's experiences of the marine phenomena occurring on Wednesday, 6 June 1917 at 6.00 pm. The other is a contemporaneous weather description found in *The Telegraph*, which is more descriptive than that available in BoM records. The anecdotal account describes the noticeable rapid onset of large surf, the force of the currents, the related weather conditions and the duration of over 12 hours, together with the loud-sounding noise of waves.

Proposed Meteotsunami, 6 June 1917 – Weather Synopsis for Brisbane, 6 June 1917

The Telegraph, Wednesday, 6 June 1917, p. 4 (Anon., 1917a):

"Weather Reports.

"Intense Anticyclone.

"The small anticyclonic nucleus which existed over south eastern Queensland and north eastern New South Wales has not moved in the last 24 hours, but it has contracted considerably … An interesting feature of the chart is the sudden development of a tropical disturbance. Last Saturday's chart gave some indication of the formation of a depression between the far northern coast of Queensland and the Solomon Islands. Instead of approaching our north eastern coast, it appears to have moved on a south easterly course at a great distance from our seaboard, and to-day, there is no doubt whatever that it exists with a considerable degree of intensity between Sandy Cape and New Caledonia, the centre at 9 a.m. to-day being approximately west-south-west

from Noumea … It is interesting to note that it has made progress in spite of the intense anti-cyclone before referred to, and if the latter should maintain its position and intensity during the next 21 hours, the course of the tropical disturbance will in all probability be deflected southward, and our coastal regions south of Sandy Cape may experience showery and somewhat squally conditions under the influence of its south-east quadrant."

Meteotsunami of 3–4 December 2016 (Causal Trigger: Local 'Super Cell' Weather System)

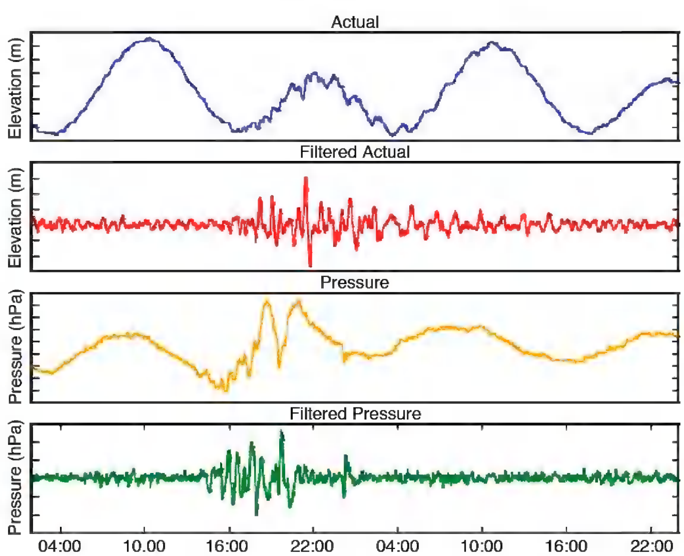
The scientific description of this event is explained by Metters (2019):

> Meteorological tsunami (or meteotsunami) have characteristics similar to earthquake generated tsunami, however the driving force behind them are air pressure disturbances associated with fast moving weather systems. A meteotsunami generated by a fast moving severe thunder storm was reported along the east coast of Australia in December 2016. The meteotsunami wave speed, it's [*sic*] driving force and general characteristics are described here. The meteotsunami was recorded in coastal South-East Queensland water level stations in Moreton Bay, Brisbane River, and Gold Coast and in Gold Coast waterways. The driving mechanism behind the meteotsunami is described as the change in atmospheric pressure as the thunder storm travelled across the coast. The pressure step ranged from 5.5 hPa to 9.9 hPa over 18 to 99 minutes. The meteotsunami signal travelled up to 10.6 m/s within the Brisbane River and slowed as it travelled upstream to 5.8 m/s in the upper reaches and into the Bremer River. Meteotsunami wave height ranged from 0.13 m to 0.46 m.

The quantitative measurements of Figure 6 show a tide gauge sea level and barometric pressure recorded meteotsunami of 3–4 December 2016; the chart illustrates four traces:

- Chart 1: The actual tide gauge plot (24-hour high and low tides) with the superimposed disturbance of the meteotsunami over 10–12 hours, and a maximum of 0.41 m wave height.
- Chart 2: Where the diurnal tide effect is filtered, illustrating the meteotsunami effect.
- Chart 3: Barometric pressure disturbances.
- Chart 4: Barometric pressure disturbances, filtered.

Figure 6. Meteotsunami records for South East Queensland (3–4 December 2016) – water level and atmospheric pressure at Southport Beach, non-filtered and high-pass filtered.



A Bureau of Meteorology weather synoptic chart (Figure 7) shows the progress of a low-pressure trough that caused thunderstorms in the Brisbane region. A YouTube video gives an awesome presentation of the weather phenomena that caused the meteotsunami of 3 December 2016 (PCR Aerial Photography, 2016).

The significance of recognising these meteotsunami phenomena in South East Queensland is their causal relationship with the growing incidence of super cell thunderstorms and east coast lows (October–January) as mentioned in the introduction. The plot in Figure 8 shows their steady increase over the last three years.

Table 2. Comparative descriptors of common features of two meteotsunami events in South East Queensland.

Event date	**Tide gauge record**	**Duration**	**Wave height & period**	**Areal extent**	**Phenomena reports**	**Literature cited**
3–4 December 2016, 2.00 pm	36 tide records	10 hours	0.4 m; 10–50 minutes	Burnett Heads to Tweed border and 50 km up Brisbane River	Synoptic weather: The first storm (supercell thunderstorm) swept through Brisbane's CBD, Brisbane Airport, Nudgee, Samford and Albany Creek about 5.25 pm, before moving north-east all the way through to waters off Bribie Island. Another storm cell hit Boonah, Laidley, Gatton, Esk's west and south-west, and Burpengary and Brighton about 5.50 pm.	DSITI publication, February 2017 (Anon., 2017). Meteorology report, ABC News (McLeish & Staff, 2016). BoM December 2016 climate report (Bureau of Meteorology, 2017).
6 June 1917, 6.00 pm	None readable	12 hours	1.25–2.5 m State of sea: "4"	Caloundra to Stradbroke Island	Without any apparent reason, the air being comparatively still, a heavy swell suddenly set in, and by midnight great breakers were rolling in heavily on the beaches. The state of the sea was officially recorded as "4". The booming of the mountainous breakers on Moreton and Stradbroke islands was so plainly heard in Wynnum and Manly, 17 to 20 miles away, that the sleep of a number of residents was disturbed. Synoptic weather: "The small anticyclonic nucleus which existed over SE Queensland and NE New South Wales has not moved in the last 24 hours, but it has contracted considerably."	*The Brisbane Courier*, Friday, 8 December 1917 (Anon., 1917b). *The Telegraph*, Wednesday, 6 June 1917 (Anon., 1917a).

Figure 7. Synoptic chart of MSLP several hours before passage of a low-pressure ridge passing over New South Wales and Queensland, from December 2016 monthly weather summary (Bureau of Meteorology, 2017).

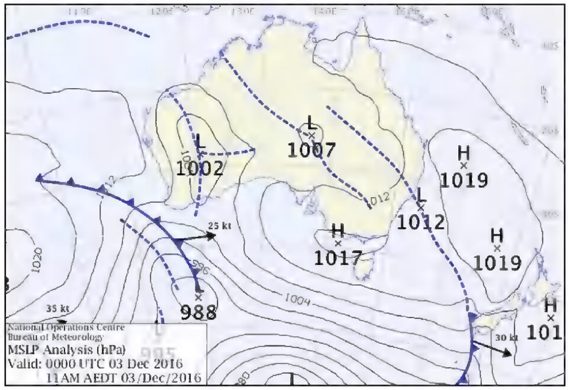
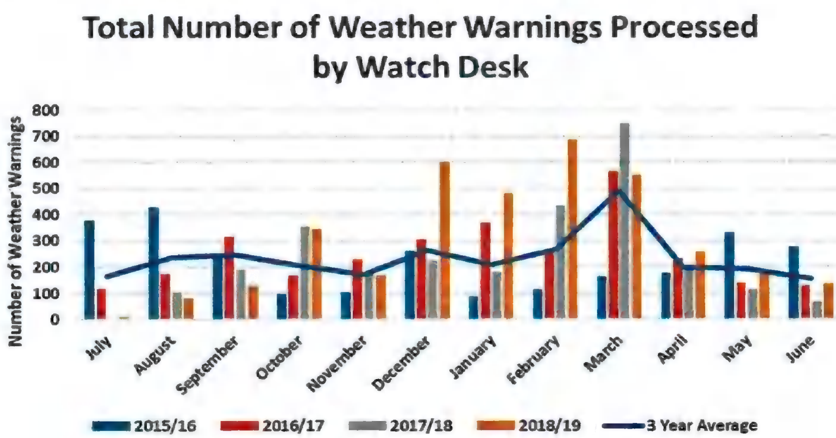


Figure 8. 2015–2019 comparison of number of weather warnings issued by the State Disaster Coordination Centre, with a 3-year roving average (Tot & Pringle, 2019).



Discussion

As a citizen scientist, I have presented some examples of the documented evidence for historical tsunami occurrences, access to which relies on the record's preservation and online accessibility to charts, old newspapers, data and research papers, which are over one and a half centuries old. Access to peer-reviewed journals was also required. We can now appreciate the scale of digital storage required to bring all these primary objects of science and documentary information together. Such ongoing access will allow a digital researcher to reappraise and assess the natural phenomena of reoccurring tsunamis.

Interestingly, newspaper clips presented in this paper were gathered and digitally processed by a public agency (Trove, Australian National Library), providing a large and visionary project for the whole of society. It is a costly process to maintain public access to such sources, involving consciously and professionally auditing our retrospective knowledge base. Interestingly, the Trove newspaper database can only provide access up to 1955. Later editions are proprietary owned, in this

era of newspaper closure. Will that knowledge ever be preserved? The Trove project's funding ceased in 2016 (Jones & Verhoeven, 2016).

I have discussed cases where the public service is not meticulously preserving its own scientific data suites for future analysis. Professional engineers have also expressed similar concerns that data preservation and archiving are not occurring. It has been observed by the professional body Engineers Australia (formerly The Institution of Engineers Australia, or IEAust) that:

> According to a paper released by IEAust's National Committee on Coastal and Ocean Engineering, there is a worrying trend in the Australian public sector which is seeing data collection programs lapse as governments devolve their work to the private sector (Gordon, 1993).

Similarly, in 1994, Mr Rob Tucker, a previous chairman of IEAust's Coastal and Ocean Committee wrote:

> Australian governments are developing a casual attitude to data monitoring – partly because there have been so few disasters over the past two centuries and we are complacent about the risks (Tucker, 1994).

A Royal Society of Queensland researcher, David Marlow, observed in his recent paper:

> A public sector shorn of such capabilities can no longer contribute as it should to government decision making. The end result will inevitably be misdirected governmental priorities and flawed governmental decisions. When scientific advice – almost always cautious, given scientists' natural reliance on demonstrable evidence – is discarded, there is the risk of wide-spread and often permanent environmental damage and inadequate management of increasingly stressed ecosystems. Society in general will suffer as problems unnecessarily persist, because opportunities have been lost and resources and funding wasted. The problems themselves become less amenable to solution, because of the loss of focus in addressing them – and the loss of skilled personnel to address them.
>
> However, the cruellest cost is wasted time – priceless, irrecoverable time – where genuine progress to a better future for the state or the nation is erased as if it had never existed (Marlow, 2019).

The Australian Government's regulated record-keeping process is designed for business records (fiscal and HR administrative files) which are utilised by all agencies, but it is driven more by the cost savings derived from less floor space for paper file storage. There is a concern that all levels of government emphasise the digitisation of their business records in order to conform to regulations requiring conversion of paper records into knowledge-management information systems. Such a business focus is very skewed and not widely comprehended.

Government regulatory prescriptive archival retention guidelines (legal file destruction) are devised by respective record-keeping agencies whose expertise originates from old public service filing systems. One would be hard pressed to find a preservation or retention category that reflects the longitudinal preservation value of the daily scientific tide chart and the daily seismograph or synoptic weather charts. These are, nevertheless, all classified as public documents. To deliberately destroy such records, by neglect or wanton vandalism, is a criminal offence.

Is this short-sightedness the result of faulty archival directives, or a public service cultural artefact? In a study on the introduction of computers to the Queensland Public Service, the State Planning Officer (Mr Ken S. Pope) observed: "I found the public service to be rigid and highly structured. This explains to some extent the delays I received in trying to get the computer going (Pope 1997: pers. comm., 4 November)" (Kelk, 2001).

A study of the Commonwealth Bureau of Meteorology (Gardner, 1997) best explains the causal origins of lack of scientific expertise in the modern 'shop front' public service. This brief snippet does little justice to that author's interesting work:

> Unfortunately for the Bureau, the fact that it came under the purview of the Public Service Board (PSB), even though it had its own Act of Parliament, meant that it could not obtain permission to employ research scientists, despite

an intense lobbying effort supported by its minister and departmental secretary. The PSB mandarins were less than amenable. They were not prepared to follow the precedent set by the employment of research scientists within the Department of Supply and allow bureau staff access to the same arrangements, apparently because it was judged to be inappropriate at the time (confidential comment to Gardner, 1997).

Conclusion

Earthquake and tsunami observational research is sorely needed in Queensland, for scientific, engineering and urban hazard planning reasons. Engineers and scientists must be better prepared (at undergraduate level) to preserve and consciously curate and protect their project data by moving it to digital archive-compatible information platforms. They must proactively re-educate their chief archival and information technology (IT) officers on the long-term (100-year) preservation requirements for existing scientific data repositories, analogue charts and databases, and the related metadata used to calibrate those charts. They must also implement an information management audit plan, documenting which IT operational programming and digital data backups were used in their research. Such a schema was introduced as mandatory in 2019 for the Commonwealth Grants Scheme administered by the Australian Government Department of Education and Training (Dodd, 2020). It must be carried forward with each new hardware system changeover.

In summary then, unlike politicians or public servants, both engineers and academic scientists operate under codes of conduct or ethics:

> All practitioners are expected by the community to act responsibly in their professional duties associated with the coastal zone. This includes the concept of being fit and proper, by virtue of training and experience, to undertake such work whether for reward or not. They are expected to devote the requisite time to each particular undertaking so as to render an outcome that would be considered "competent". In particular, it is their duty to maintain awareness of the current state of the art of their profession and to obtain specialist advice whenever necessary. Engineers are required by their Institution to act in a manner that accelerates achievement of sustainability (NCCOE, 2004).

Learned Societies, such as The Royal Society of Queensland, are also setting high standards by providing new digital platforms (Queensland Science Network) for citizen scientists to preserve collection data and filed analysis, for re-use by other researchers.

What does an international standard for preserving observational data look like? This paper has exemplified, in a small way, the rich knowledge inter-relatedness of tsunami data, climate data sources, newspaper records and observational sources, both historical and future, which will allow modern climate researchers to build a Hazard Recurrence Interval schema, through data-mining techniques enabled by super-computer facilities. This knowledge schema can be utilised by the wider academic community and even the general public, in multiple disciplines of study. Figure 9 graphically represents the global aspirational development currently taking place. In addition to the climate typology classification already discussed, there are systems developed by the International Atmospheric Circulation Reconstruction (ACRE) researchers (e.g. Williamson et al., 2015), as well as the European FAIR data principles (Findable, Accessible, Interoperable and Re-usable) being adapted internationally. Resistance to their adaptation (David, 2020) derives from *not* recognising basic record-keeping practice and adapting the data re-use ethos that is contrary to old academic 'secrecy' practice. That is another story realm for a later day.

As a quick and final prompt, I reiterate that storage is not preservation because (Harrower et al., 2017):

- What you store can be corrupted or the storage media can fail, causing data loss.
- As technology and software change, data can become technologically inaccessible.
- Files 'saved' on their own may not be findable by search procedures; they need metadata to allow us to find them.
- Any kind of file needs context to make it meaningful, such as dates, subjects, titles, authors, and name of platform.

Figure 9. Summary diagram of the integrated approach to the analysis of hazards from different records and archives of differing time-frames, which can be adapted to tsunamis and volcanoes (from Williamson et al., 2015, Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License).

Glossary

(After Harper, 1998; Hughes, 2020)

AHO (Australian Height Datum). This datum has been adopted by the National Mapping Council as the datum to which all vertical control for mapping is to be referred. It is approximately equivalent to Mean Sea Level (MSL).

Ambient pressure. The MSL atmospheric pressure surrounding, but not affected by, a tropical cyclone.

Astronomical tide. The periodic rising and falling of the oceans, resulting from the gravitational attraction of the Moon, Sun and other astronomical bodies acting upon the rotating Earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the 'tide', it is preferable to designate the latter as the tidal current, reserving the name 'astronomical tide' for the vertical movement.

Bathymetry. The measurement of depths of water in oceans, seas and lakes; *also*, information derived from such measurements.

Continental shelf. The zone bordering a continent and extending from the tidal low water mark to a depth where there is a marked or rather steep descent towards greater depths.

Coriolis effect. The influence of the Earth's rotation that causes winds to circulate in a clockwise direction around low-pressure systems in the southern hemisphere.

El Niño southern oscillation. Large-scale natural fluctuation in the global climate system that occurs irregularly and involves a close coupling of the oceans and atmosphere.

HAT (Highest Astronomical Tide). The highest level that can be predicted to occur under average meteorological conditions and any combination of astronomical conditions. These levels will not be reached every year, HAT generally occurring at any one location once every 18.6 years.

Inverse barometer effect. The proportional rise in water level due to the hydrostatic pressure deficit beneath a tropical cyclone. The pressure deficit is the difference between the MSL ambient pressure and the MSL pressure at the centre of the tropical cyclone. The local magnitude of the rise in elevation is approximately 10 mm per 1 hPa of pressure deficit.

Long-wave motion. A class of surface disturbances of the sea surface whose characteristic wavelength (distance between consecutive peaks or troughs) is such that the resulting motion can be considered as nearly horizontal in form. Long waves include the astronomical tide, storm surge and tsunamis.

MSLP (Mean Surface Level Pressure). The surface pressure reduced to sea level. Solid lines are isobars, i.e. lines of equal MSLP. These charts show surface pressure patterns – areas of high and low pressure which are associated with different weather types. Usually, low-pressure systems (cyclones or depressions) bring unsettled weather whilst high-pressure systems (anticyclones) are associated with settled weather. In the northern hemisphere the air rotates counterclockwise around the low-pressure centres and clockwise around the high-pressure centres (the opposite applies in the southern hemisphere). Wind speed is roughly proportional to the distance between isobars: so closely packed isobars mean strong winds, and vice versa.

Radius of maximum winds. The distance from the centre of a tropical cyclone, where winds are calm, to the point where the surface wind speeds are greatest (at the position of maximum radial pressure gradient).

Return period. Also known as average recurrence interval or ARI. The return period of an event, normally expressed in years, is the average time between successive events of equal or greater magnitude. The actual time between such events may be greater or less than this period due to the randomness of the process. The inverse of the return period is the average annual probability of exceedance, which remains constant from one year to the next, regardless of whether a given event has or has not occurred.

Sea is generated by local winds at the time of observation. It is characterised by short, discontinuous crest lengths that are closely spaced and often associated with white capping.

Spring tidal range. The difference in height between MHWS (mean high water springs) and MLWS (mean low water springs). MHWS is the long-term average of the heights of two successive high waters during those periods of 24 hours (approximately once per fortnight) when the range of tide is greatest, at full and new moon. MLWS is the long-term average value of two successive low waters over the same period as defined for MHWS.

Storm surge. A rise above normal water level on the open coast due to the combined effects of surface wind stress and atmospheric pressure fluctuations caused by severe weather events (e.g. tropical cyclones).

Storm tide. The combined action of storm surge and astronomical tide.

Swell has travelled to the coast after being generated by winds at a distant location. It is characterised by long, continuous crest lengths. At times, particularly during storms, there may be a coincidence of both sea and swell.

Tropical cyclone. Also known as a hurricane or typhoon. An intense, large-scale low-pressure storm system of tropical origin with cyclonically rotating mean winds at the sea surface (clockwise in the southern hemisphere) in excess of gale force (63 km/hr, 34 kt, or 17.5 m/s).

Tsunami. Tsunami is a Japanese word: *tsu* meaning harbour and *nami* meaning wave. A transient long-period wave typically caused by an underwater disturbance such as an earthquake, volcanic eruption or landslide. Tsunamis can travel very long distances across oceans and affect remote coasts, often being amplified as they enter shallow waters, and are capable of significant inundation. Tsunamis are sometimes incorrectly termed tidal waves.

Wave runup. The rush of water up against a structure or beach on the breaking of a wave. The amount of runup is the vertical height above still-water level to which the rush of water reaches. In the present report, runup is measured from the quasi-steady wave setup level.

Wave setup. A quasi-steady super-elevation of the water surface due to the onshore mass transport of water caused entirely by the action of breaking waves. Wave setup is sometimes included in calculations of wave runup.

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Author Profile

Colin Lynam retired from The University of Queensland Seismograph Stations (UQSS) in 2002 when this facility officially ceased operation. It had run a full ASRO observatory at Charters Towers (1957–1998) and a standard observatory at Gardens Point and then Mt Nebo, Brisbane (1935–2018). This was a unique era to be working in seismology as those observers became the United Nation's policeman's eyes of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), continuing even today. It was also the era in which the first global seismograph station networks were deployed, and UQSS became aware of our own earthquake history and community awareness. Colin is an active citizen scientist, contributing a science communication blogging service for the Australian Earthquake Engineering Society (Engineers Australia) and communicating/writing with expert groups within The Royal Society of Queensland.

Vegetation Change Over 50 Years in Eucalypt Forest on North Stradbroke Island

Paul Williams[1], Dave Kington[2], and Eleanor Collins[1]

Abstract

Detailed vegetation surveys on North Stradbroke Island (known by Traditional Owners as Minjerribah) by University of Queensland botanists in 1967 provided a rare and valuable opportunity to assess vegetation composition and structure changes over the last 50 years. The eucalypt forest assessed is dominated by scribbly gum (*Eucalyptus racemosa*), representing Regional Ecosystem 12.2.6. It is the most widespread forest on the island and is also abundant on Moreton and Fraser Islands, as well as the Cooloola Coast, so that this evaluation is relevant to a broad area. At the forest site, located south of Brown Lake, a previously continuous ground cover of kangaroo grass (*Themeda triandra*) has all but disappeared, while other herbaceous plants and species richness have declined. Large shrub and small tree densities have dramatically increased, particularly *Allocasuarina littoralis* and *Leptospermum trinervium*. Eucalypt crowns have been damaged and several trees are dead. The forest south of Brown Lake was burnt by intense fires in 1965 and 1995, but was not burnt in the extensive January 2014 wildfire. The study site may have experienced other fires which have not been documented, but was long unburnt by the time of the 2016 survey. We suggest that the dramatic loss of grass and herb cover, shrub and small tree thickening, plus crown damage, resulted from irregular, high-intensity fires. The re-establishment of regular, low- to moderate-intensity fires during periods of good soil moisture is likely to reduce crown damage, maintain shrubs at a healthy density and promote native grasses.

Keywords: eucalypt forest, wildfire, cultural burning, burning regime, planned burning, vegetation condition, kangaroo grass, *Themeda triandra*

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Introduction

North Stradbroke, known by the Traditional Owners as Minjerribah, is a sand island east of Brisbane, 11 km offshore from Cleveland. Eighteen regional ecosystems (REs) are mapped across the island, dominated by eucalypt forests, wetlands and heaths (Stephens & Sharp, 2009). The most abundant eucalypt forest is RE 12.2.6, *Eucalyptus racemosa* on sand dunes and plains, while the mallee-heath RE 12.2.10 of *Eucalyptus planchoniana*, *Corymbia gummifera*, *E. racemosa* and *Banksia aemula* is abundant across the island's central ridges (Queensland Herbarium, 2019). These communities are abundant on nearby islands and the Cooloola Coast. Many large trees on the island have been dated as several centuries old, and traditional, low-intensity burning is thought to have preserved these old trees (Ngugi et al., 2020).

University of Queensland staff (Professors Trevor Clifford and Ray Specht) and students undertook botanical surveys on North Stradbroke Island in the mid to late 1960s, with further research through the 1970s and into the 1980s. They surveyed eucalypt forests and heaths south of Brown Lake and north of Blue Lake, and mallee-heaths on Mt Hardgrave,

describing them as characteristic representations of habitats of the inland sand dunes of the island (Clifford et al., 1979). Their survey results were written up in scientific articles and also as a book (Connor & Clifford, 1972; Clifford et al., 1979). Their vegetation surveys provide a valuable baseline for the assessment of vegetation change over time.

Fire is an important element in eucalypt forest dynamics. Specht et al. (1984) describe the 1965 fire in the Brown Lake area as a "ground and crown fire". Connor & Clifford (1972) refer to two fires over four years, apparently prior to their 1967 survey – presumably the 1965 wildfire and an earlier patchy fire. The Brown Lake study site was burnt again in February 1995 (Paul Smith, pers. comm., 2020). No other fires have been documented in the Brown Lake site, but it is possible that one or more undocumented fires have occurred since 1965. However, the site did not burn in the January 2014 wildfire and appeared to have been unburnt for well over 10 years by 2016, based on little charcoal and the abundance of dense fire-sensitive species (e.g. *Allocasuarina littoralis*).

An awareness of vegetation change helps guide discussions about ideal composition and structure, and possible factors governing dynamics. While management should not automatically strive for some past vegetation condition, it should appreciate that broad changes in structural and species dominance patterns, and the appearance of canopy dieback, are essential factors for defining a healthy ecosystem, for understanding how forest communities function and for determining management objectives.

Methods

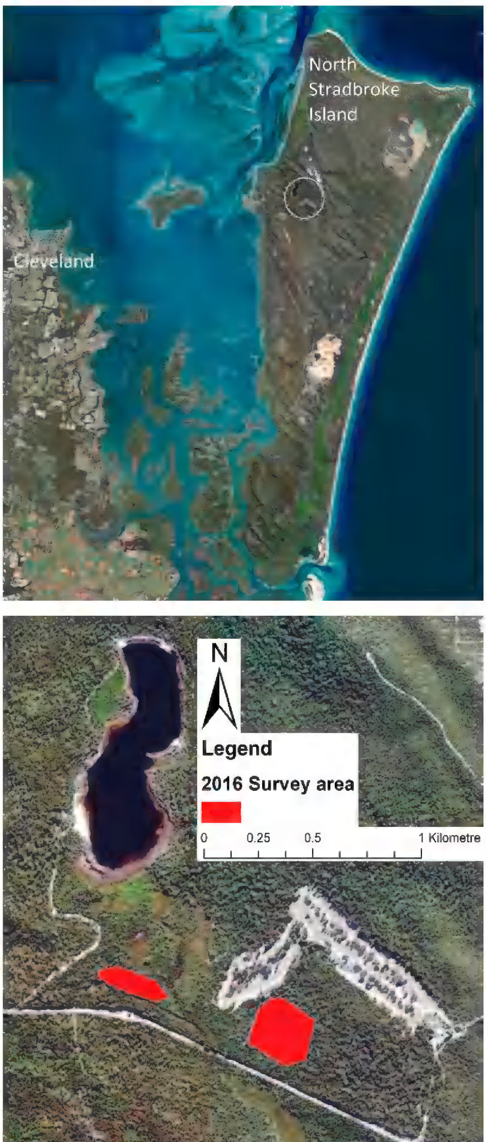
The University of Queensland (UQ) botanists produced fine-scale vegetation maps and descriptions for the ecosystems on the south side of Brown Lake (Connor & Clifford, 1972; Clifford et al., 1979). The UQ vegetation maps and associated vegetation descriptions were produced from a 1967 survey of two hundred 2 × 1 m quadrats, arranged in a grid across a 625 m × 400 m area containing a mixture of open eucalypt forests and heathy sedgelands (Connor & Clifford 1972; Clifford et al., 1979). All species present within each of the 2 × 1 m quadrats were recorded, to produce a table of species' frequency of occurrence (i.e. percentage of quadrats in which each species was present) across the area (Clifford et al., 1979). Vegetation types (eucalypt open forest and closed heath/grassland communities) were determined and mapped across the area based on the species information across the two hundred quadrats.

UQ distinguished three heathy sedgeland swamps and three eucalypt forest communities for the area south of Brown Lake, each differing in frequency of different key species. The three eucalypt forest communities were scribbly gum (*Eucalyptus racemosa*) with an understorey of kangaroo grass (*Themeda triandra*) and the small legume shrub *Phyllota phylicoides* (Community E); a forest dominated by blackbutt (*E. pilularis*) and scribbly gum with a kangaroo grass understorey (Community F); and a forest dominated by blackbutt and scribbly gum, with kangaroo grass and *Phyllota phylicoides* only rare in the understorey (Community D).

In February and April 2016, approximately 50 years after the initial UQ assessments, a resurvey was undertaken on the south-east side of Brown Lake. The 2016 assessment resurveyed, as closely as possible, the areas described in 1967 as eucalypt open forest with kangaroo grass (combining UQ Communities E and F of Clifford et al., 1979), which are south of the golf course (27.5004° south; 153.4401° east). This vegetation is RE 12.2.6, which is the most widespread forest ecosystem on the island. Since the original UQ surveys, a few tracks have been pushed through and a golf course built in the general area near Brown Lake. We repeated the 1967 survey method of recording species frequency within 2 × 1 m quadrats. In 1967, a total of 200 quadrats was sampled across six communities. We surveyed 50 quadrats to assess the eucalypt open forest areas dominated by kangaroo grass in 1967. The 50 quadrats were spread over an area 900 m wide, dissected by a wet heath, to ensure best possible overlap with the original 1967 survey area (Figure 1). Although it is difficult to know the precise boundaries of the initial UQ study site, our 2016 quadrat survey probably includes an extension of about 150 m east of the initial UQ boundary, to ensure adequate coverage of the eucalypt forest area and to compensate for the forest lost to the golf course development. Photos were taken of the site from a helicopter, and an overall assessment of the condition of the sites was made on the ground (e.g.

examining vegetation structure and crown health). Comparisons in species frequency of occurrence data and an evaluation of the descriptions provided by UQ were made to determine change over time.

Figure 1. Map of North Stradbroke Island (top, survey area circled) and 2016 survey area (below).



Results

Dramatic vegetation changes have occurred in the eucalypt forest on the south-eastern side of Brown Lake over the last 50 years. There were considerable differences in the frequency of occurrence data for common species in the open eucalypt forests in 2016 compared to 1967 (Table 1).

Note: The 1967 data are an average of records from the two grassy open eucalypt forest communities E & F described in Clifford et al. (1979), where only data from the most common species were published. Therefore, the 1967 records are presented as a blank space against some species, as we cannot be certain that their occurrence was zero.

Species with large changes between 1967 and 2016 are highlighted in bold. No alien species were recorded.

The majority of the six most abundant species in either 1967 or 2016 surveys changed in occurrence (Table 1). Two woody plants (*Allocasuarina littoralis* and *Woollsia pungens*) and the sedge *Lomandra multiflora* increased in frequency by 2016 (Figure 2). Other species that increased in frequency by 2016 were the sedge-like ground layer plant *Baloskion tetraphyllum*, as well as the shrubs *Acrotriche aggregata* and *Leptospermum trinervium*.

The largest reduction in frequency was of kangaroo grass, which declined from being present in every quadrat in 1967 to only 6% of quadrats in 2016. Furthermore, kangaroo grass was only represented by a few small, spindly tufts in those few 2016 quadrats, rather than healthy grass tussocks.

Other species that declined in occurrence between 1967 and 2016 included bracken fern (*Pteridium esculentum*) which nearly halved, and the small shrubs and herbs *Boronia rosmarinifolia*, *Bossiaea heterophylla*, *Hibbertia acicularis*, *Leucopogon* sp., *Phyllota phylicoides*, *Pimelea linifolia*, *Sowerbaea juncea* and *Strangea linearis*. The small trees *Allocasuarina torulosa* and *Banksia aemula* also decreased in frequency of occurrence.

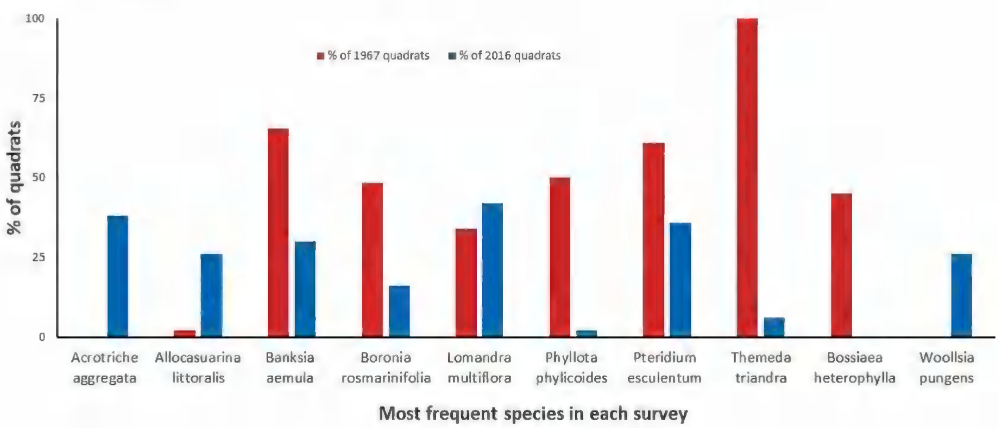
There was a dramatic decline in species richness between 1967 and 2016. The mean species richness per quadrat (2 m^2) in 2016 was 4.9 species. This is one-third of the species richness (15 species, per 2 m^2) recorded by Connor & Clifford (1972) as an average from their quadrats surveyed in 1967.

Table 1. The percentage frequency of occurrence within 50 quadrats of all species in eucalypt forest in 2016, compared with their frequency in 1967.

Family	Species	1967 quadrats (%)	2016 quadrats (%)
Apocynaceae	*Parsonsia* sp.		4
Casuarinaceae	***Allocasuarina littoralis***	**2**	**26**
	Allocasuarina torulosa	**17**	**2**
Cupressaceae	*Callitris rhomboidea*		2
Cyperaceae	*Fimbristylis* sp.		14
	Lepidosperma laterale		2
Dennstaedtiaceae	***Pteridium esculentum***	**61**	**36**
Dilleniaceae	***Hibbertia acicularis***	**39**	**4**
Elaeocarpaceae	*Elaeocarpus reticulatus*		10
	Tetratheca thymifolia		2
Ericaceae	***Acrotriche aggregata***		**38**
	***Leucopogon* sp.**	**36.5**	**6**
	Woollsia pungens		**26**
Euphorbiaceae	*Ricinocarpos pinifolius*		10
Fabaceae	***Bossiaea heterophylla***	**45**	**0**
	Daviesia umbellulata		2
	Dillwynia retorta		2
	Phyllota phylicoides	**50**	**2**
Hemerocallidaceae	*Dianella* sp.		10
Lauraceae	*Cassytha*		8
Laxmanniaceae	***Lomandra longifolia***	**40.5**	**2**
	Lomandra multiflora	**34**	**42**
	Sowerbaea juncea	9.5	0
Myrtaceae	*Angophora leiocarpa*		6
	Austromyrtus dulcis		6
	Corymbia intermedia	4.5	10
	Eucalyptus pilularis	10	2
	Eucalyptus planchoniana		8
	Eucalyptus racemosa	19	18
	Leptospermum trinervium	**2.5**	**22**
	Ochrosperma lineare	4.5	6
Poaceae	*Eriachne pallescens*		2
	Themeda triandra	**100**	**6**

Family	Species	1967 quadrats (%)	2016 quadrats (%)
Proteaceae	***Banksia aemula***	**65.5**	**30**
	Persoonia virgata		6
	Strangea linearis	26	0
Restionaceae	*Baloskion pallens*		2
	Baloskion tetraphyllum	**3.5**	**22**
	Empodisma minus		6
	Leptocarpus tenax		4
Rutaceae	*Boronia rosmarinifolia*	48.5	16
	Zieria smithii		2
Sapindaceae	*Dodonaea triquetra*		4
Schizaeaceae	*Schizaea bifida*		8
Thymelaeaceae	***Pimelea linifolia***	**40**	**0**
Xanthorrhoeaceae	*Xanthorrhoea johnsonii*	30.5	22
Other plants	Herbs unidentified		14

Figure 2. The change in frequency of occurrence (percentage of quadrats) between 1967 and 2016 for the most common species in each survey.



The original UQ quadrat data were complemented by observations of vegetation structure. The vegetation described by Connor & Clifford (1972) and Clifford et al. (1979) as open eucalypt forest with a kangaroo grass ground layer was by 2016 a forest with very dense shrubs and small trees, and almost no grasses (Figure 2). By 2016, the forest contained a number of dead trees and dead trunks with coppice shoots (Figures 3, 4 and 5). It was estimated from a recent aerial photo that approximately 13 trees per hectare have a badly damaged crown or are dead. Several trees have old fire scars, so the crown-damaged and dead eucalypts probably represent damage from the 1965 and/or 1995 fires.

Figure 3. In 2016, the eucalypt forest had dense shrubs (top) with a ground layer dominated by leaf litter and *Austromyrtus dulcis* (bottom); this is in contrast to the description of an open forest with an abundant kangaroo grass layer in 1967.

Figure 4. Photo taken on 28 April 2016 from a helicopter looking north-east across the Brown Lake study area (top); and a recent aerial image (bottom). Several dead eucalypt trunks can be seen, as can the darker-green *Allocasuarina littoralis* trees. The dead eucalypt trunk (circled) is the eucalypt with coppice shoots shown from the ground in Figure 5.

Figure 5. An example of the many dead trunks in the area, apparently killed by the 1995 wildfire. This eucalypt, with coppice shoots, is the one marked by a black circle in Figure 3.

Discussion

The change in vegetation composition and structure to the south of Brown Lake since 1967 has been considerable. Clifford et al. (1979) reported kangaroo grass dominating the ground layer of open eucalypt forest, with 100% presence within their eucalypt forest 2 × 1 m quadrats. This equates to a well-grassed, open forest. The UQ description of the site as an open eucalypt forest reflects that of locals, including Greg Litherland (pers. comm., 2016) who recalls his father being able to drive a Bedford truck through the open eucalypt forest south of Brown Lake in the 1950s. Westman & Rogers (1977) also describe a scribbly gum open forest with blady grass, wire grass (*Aristida* spp.) and kangaroo grass in their 1973 survey south of Point Lookout. In their study of forest biomass, grasses and other herbs contributed a third of understorey living biomass (equal to both shrubs and tree saplings). Therefore, it is apparent that open eucalypt forest with native grasses and scattered shrubs was once widespread across North Stradbroke Island. This open, grassy forest structure has disappeared from the Brown Lake site and is currently rare on North Stradbroke Island.

Specht et al. (1984) stated that kangaroo grass was frequent at their site near Brown Lake in 1976 (note that this was 11 years after the 1965 fire) but had almost disappeared by 1984 (19 years after the fire). Specht et al. (1984) also documented a decline in kangaroo grass biomass from 11 g/m^2 in 1976 to only 1 g/m^2 in 1984 (in the unfertilised control part of their experiment). By 2016, there remained only a few very thin and scattered kangaroo grass tufts.

Specht et al. (1984) found that the loss of native grasses near Brown Lake was associated with an increase in shrub and small tree biomass, primarily *Allocasuarina littoralis* and tea tree (*Leptospermum trinervium*). They recorded that *Allocasuarina littoralis* and other shrubs regenerated by seedlings following the 1965 fire, with *Allocasuarina littoralis* increasing in frequency of occupancy six-fold between 1968 and 1984. The post-fire *Allocasuarina littoralis* seedlings progressively grew to form a mid-stratum layer that, with the eucalypt canopy, "slowly suppressed the ground layer" (Specht & Specht, 1989). This smothering of the ground-layer plants in the Brown Lake eucalypt forest resulted in a progressive decline in species diversity following the 1965 fire: from around 26 species per 10 m^2 after four years; to around 23 species after 11 years; and around 18 species after about 18 years (Specht & Specht, 1989).

Considerable crown damage and some tree death is apparent south of Brown Lake, presumably as a result of the intense 1965 or 1995 fires. An island-wide assessment after the 2014 wildfire found widespread eucalypt canopy damage and tree death, as well as high densities of shrub and small tree recruitment, with limited grass cover (Williams et al., 2016). The presence of healthy trees, several centuries old, scattered across the island suggests that preservation was provided by traditional, low-intensity burning by Aboriginal people (Ngugi et al., 2020). The loss of regular burning allows the development of high fuel

loads and intense wildfires, which can damage tree crowns.

In summary, the process of vegetation change near Brown Lake appears to be that intense fires in 1965 and 1995 promoted the recruitment of many shrub and small tree seedlings which, during long intervals between fires, grew to form a dense mid-stratum that shaded out grasses and herbs, clogging the previously open forest structure and reducing species diversity. The intense fires also damaged eucalypt crowns and killed some trees. It appears probable that the promotion of a dense shrub layer is likely to form a fuel ladder that promotes the scorching of the canopy in future fires, unless the burns are skilfully implemented at times of good soil moisture.

The proposed mechanism of vegetation change is that intense fires during dry conditions damage grasses, while promoting dense shrub and small tree recruitment. The shrubs and small trees grow into dense ladder fuels that shade grasses and can draw flames into the canopy to damage eucalypt crowns. This promotes further dense shrub recruitment, which grows into dense thickets during subsequent long fire intervals, perpetuating the cycle. The loss of native grasses makes early-season, low-intensity fires more difficult to implement.

We propose that fire intervals in RE 12.2.6 should typically be every two to six years (rather than the currently recommended seven to 25 years; Queensland Herbarium, 2019), with mosaic burning creating some longer unburnt patches. Burning must be implemented while there is good soil moisture and mild weather conditions, using spot ignitions and slowly ignited, short drip-torch lines, to ensure fire intensity remains low to moderate.

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The Benefits of Community and Stakeholder Driven Fish Monitoring Projects in a Murray-Darling Basin River

Adam Kerezsy[1]

Abstract

River and catchment management in Australia's Murray-Darling Basin underwent a transformation in the latter part of the twentieth century, from being focused on delivering water predominantly for human and agricultural needs to also considering environmental considerations. The main driver of this change was the realisation that a comparatively long period of river regulation and associated alterations to natural systems had resulted in negative consequences. Native fish communities, in particular, have been considered to be in a poor or degraded condition. The centrally located Lachlan River, in New South Wales (NSW), is a poignant example, as the fish community has been rated as 'extremely poor' in both of the basin-scale Sustainable Rivers Audit reports in 2008 and 2012. River management can generally be regarded as a top-down process, with the Murray-Darling Basin Authority and state-based agencies simultaneously relied on and looked to for advice, but also blamed for any perceived problems and inequities. However, neither the federal nor state governments and their agencies have the capacity to undertake accurate monitoring of individual catchments at localised scales. In order to achieve this, local communities and stakeholders can make a difference to the management of their catchments by actively sponsoring and participating in sampling and monitoring projects that can then inform broader catchment management. This process has begun with positive results within the Lachlan catchment, and offers a representative case study that can be applied to other areas within the Murray-Darling Basin.

Keywords: Lachlan River, off-river areas, Lake Cargelligo, Booberoi Creek, community involvement, fish surveys, endangered species

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Introduction

In Australia's heavily modified Murray-Darling Basin (M-DB) in the nation's south-east, rivers were historically managed (from the mid-1800s) in order to ameliorate the effects of Australia's unpredictable weather systems and ensure that water could be supplied for towns and agriculture and – somewhat later – for the establishment and sustenance of irrigation districts and the generation of hydroelectricity.

Due to Australia's dry climate, the principal tools for controlling flows in the M-DB were (and remain) large headwater dams that enabled flows from the highest-rainfall areas to be harvested and stored, and a series of smaller weirs or other structures situated at various points downstream that similarly enabled water to be prevented from following riverine channels until it was required (Water Conservation and Irrigation Commission, 1971). Today, there are very few rivers in the M-DB that are unaffected by such regulation (a notable exception is the Paroo River in far western Queensland and New South Wales; Kingsford & Thompson, 2006).

By the latter part of the twentieth century, and facilitated by evolving areas of study within applied science and ecology, it became obvious that the regulated rivers of the M-DB were affected by

a range of negative issues, including damming of rivers preventing natural flows, the introduction and spread of alien species, over-allocation of water, riparian denudation, pollution, and the decline of native fish species and stocks (Arthington, 1991; Walker et al., 1995; Humphries et al., 1999; King et al., 2003; Koehn, 2004). However, these issues were also complicated by geographic location, for the basin occupies four Australian states and one territory: Queensland, New South Wales, Victoria, South Australia and the Australian Capital Territory. Within each jurisdiction, agencies with associated responsibilities (water, planning, natural resources and fisheries) worked autonomously to develop 'their' rivers and associated infrastructure. However, within 100 years it became necessary to create an over-arching organisation, first called the Murray-Darling Basin Commission (MDBC) and then the Murray-Darling Basin Authority (MDBA), as it became obvious that addressing basin issues at basin scale was essential.

The observed problems were also confounded by a general absence of historical records that documented these perturbations in a quantitative manner (the survey work of J. O. Langtry, in Cadwallader, 1977, being a notable exception). Given that fish are the ecological focus of this paper, a dataset that illustrates native fish decline in the M-DB is the commercial catch data from New South Wales (Reid et al., 1997). From 1947 (when records commenced) the catch records for three of the four native species targeted by commercial fishers (Murray cod, *Maccullochella peelii*; silver perch, *Bidyanus bidyanus*; and freshwater catfish, *Tandanus tandanus*) plummeted by the 1970s (Reid et al., 1997). Following a peak in 1960 (80 tonnes), Murray cod capture fell rapidly and stabilised to less than 10 tonnes per year within seven years. Silver perch peaked in 1958–1959 with a catch of 44 tonnes, but the fishery was exhausted by 1984–1985. Catfish were similar: 43 tonnes in 1974–1975 and complete decline by 1990. This compelling evidence led to the closure of the inland riverine commercial fishery for native species in September 2001 and is indicative of the wider problems within the basin by that time (Lintermans, 2007).

The imposition of a top-down framework to manage the M-DB (including the MDBA and state government agencies, supported by research by universities and other groups) has often led to friction between jurisdictions and – most noticeably – anger within local riverine communities who sometimes feel affronted by this approach. Graphic examples include irrigators in Griffith, New South Wales publicly burning copies of the draft Murray-Darling Basin Plan in 2010 (Australian Broadcasting Commission, 2010), and the worldwide media reaction to fish kills in the Darling River near Menindee in the summer of 2018–2019 (*The Guardian*, 2019). A more consultative approach to managing these rivers is therefore clearly desirable.

The Lachlan catchment is the geographic focus of this paper and is centrally located in the basin within NSW (Figure 1). It is the northernmost catchment in the southern M-DB, the fourth-longest river in Australia, and somewhat unique within the M-DB as it most usually reaches a terminus in the Great Cumbung Swamp (near Oxley), so is essentially an isolated catchment. The Lachlan rises in the Great Dividing Range west of Sydney, and the headwater reservoir – Wyangala Dam – harvests water from both the upper Lachlan and Abercrombie Rivers.

With the exception of the native species caught by commercial fishers and targeted by recreational and illegal fishing (those mentioned above and golden perch or yellowbelly, *Macquaria ambigua*), there is limited historical knowledge of the fish communities within the Lachlan catchment (Roberts & Sainty, 1996; Trueman, 2011). Indeed, the first published record of species within the Lachlan did not occur until Llewellyn's survey (1983), where nine native and four alien species were detected.

In response to the realisation that fish communities within the M-DB (in particular) were declining, NSW Fisheries and the Cooperative Centre for Freshwater Ecology conducted the NSW Rivers Survey (Harris & Gehrke, 1997) in an effort to generate baseline river health data across the state. The Lachlan delivered poor results, with only six native fish species present.

The urgency of the M-DB problems prompted the MDBC/MDBA to initiate a large-scale and ambitious project – the Sustainable Rivers Audit (SRA) – in an effort to measure several indicators (fish, macroinvertebrates, vegetation and hydrology) in all major M-DB catchments. However, against

the SRA criteria, the fish theme presents sobering reading, as the Lachlan fish community consistently rates as 'extremely poor' (Davies et al., 2008; Davies et al., 2012).

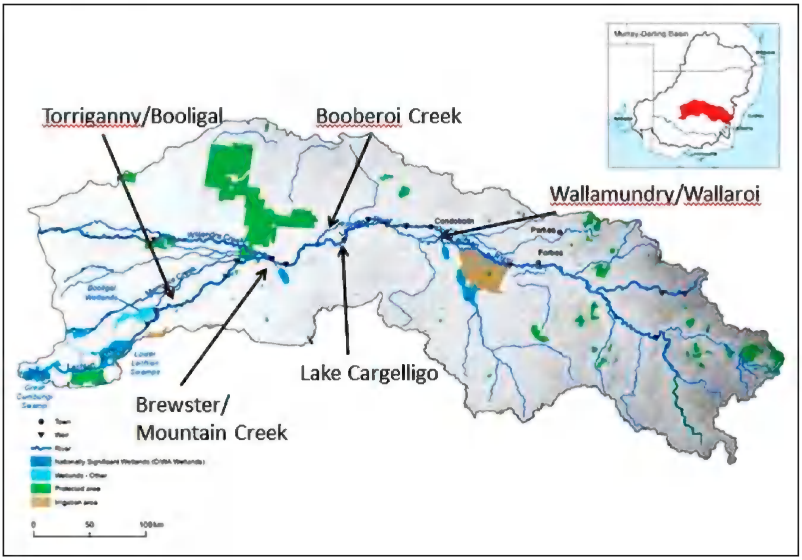
The data presented in this paper relate to fish from multiple surveys at multiple locations in the mid-Lachlan (i.e. roughly between Condobolin and Booligal; Figure 1), conducted at various times and for many different reasons between 2017 and 2020. These data have not been collected as part of a large-scale study, but instead have been sponsored and supported by local and/or regional groups – both government and not-for-profit – with an interest in auditing and then contributing to improvement of the riverine environment at local scales. The data are presented and then discussed under five headings that highlight the benefits of this 'bottom-up' approach to river management: the involvement, interest and education of local participants; the delivery of records for unknown or poorly known areas that can inform riverine management; the ecological relevance of sampling off-river areas away from the main stem of M-DB rivers; the longevity and flexibility afforded by localised monitoring; and the creation of new projects that can ensue following initial engagement. The results and discussion may, therefore, be relevant to other systems throughout the M-DB and are intended to inform future monitoring programs and management strategies.

Materials and Methods

Study Area

All fish sampling described in this paper was undertaken in what could be termed the 'mid-Lachlan' between 2017 and 2020. The sampling area stretches from Condobolin (elevation 220 m) in the east to Booligal (elevation 83 m) in the south-west, across a distance of approximately 253 km (Figure 1). As such, the mid-Lachlan represents a typical meandering, low-gradient river valley that is similar to many of the longer M-DB rivers such as the Murrumbidgee, Darling and Macquarie. The principal land use within this stretch of the Lachlan is dryland agriculture (cereal cropping combined with livestock production); however, irrigated systems are also common, with concentrations around Hillston and Condobolin producing cotton and tree crops (nuts and citrus). The climate of the mid-Lachlan is mediterranean, with long, hot summers (temperatures frequently exceed 40°C between November and March) and short, cold winters with multiple frosts.

Figure 1. Map of the Lachlan catchment. Arrows indicate areas where the fish sampling described herein has occurred between 2017 and 2020.



The mid-Lachlan is characterised by a deep (frequently deeper than 10 m) and incised main channel, and several creeks and off-river areas that are generally regulated by weirs and lock gates managed by WaterNSW. The majority of sampling was undertaken in these off-channel areas, such as the Wallamundry Creek complex close to Condobolin, Booberoi Creek between Condobolin and Lake Cargelligo, Torriganny Creek between Hillston and Booligal, and within the Lake Cargelligo system (Figures 1 & 2). Constructed from 1902–1904 by excavating channels to link low-lying areas, the Lake Cargelligo storage comprises three connected lakes that hold 36,000 ML when full. The Lake Cargelligo storage is used in conjunction with Wyangala Dam and the Lake Brewster storage to supply water to the lower sections of the Lachlan. Sampling was also undertaken at main channel sites close to the Booberoi Creek offtake and re-entry points; in the Brewster weir pool; and in Mountain Creek, which drains Lake Brewster back to the main channel of the Lachlan (Figure 1).

Sampling Rationale and Timing

The data presented do not derive from a discrete project but are the cumulative data collected from several projects that have occurred within the mid-Lachlan since 2017. As such, some sites have been sampled on multiple occasions, whereas others have been sampled only once or twice. Nevertheless, the same sampling methodology (described below) has been used during all sampling events, thus allowing the data to be used to infer general trends regarding the fish communities in this section of the Lachlan catchment.

Booberoi Creek was sampled on eight occasions between November 2017 and January 2020. The purpose of this sampling was to monitor the short- and long-term changes in the fish community following environmental flow releases by state and/or national water holders, who also enabled/sponsored the monitoring (NSW Department of Primary Industries and Environment (DPIE) and Commonwealth Environmental Water Office (CEWO)). Main channel sites in the vicinity of Booberoi Creek were sampled as an addition to Booberoi Creek sites in September–October 2019.

The Lake Cargelligo system was sampled on seven occasions between December 2017 and January 2020. The purpose of this sampling was to provide basic inventory information to a local not-for-profit group, the Cargelligo Wetlands and Lakes Council, in order to inform their management of an island (Robinson Crusoe Island) which they lease and manage for conservation.

The weir pool above Brewster Weir was sampled in both February and March 2019 and also in February 2020 in order to monitor the population of the endangered olive perchlet (*Ambassis agassizii*) that is known to inhabit this area. This work was undertaken in conjunction with volunteers from NSW ANGFA (Australia and New Guinea Fishes Association). Mountain Creek, which drains Lake Brewster back to the main channel of the Lachlan River, was also sampled in February 2019 in order to monitor the population of olive perchlet.

Yarrabandai Creek and Wallamundry Creek (both close to Condobolin) were sampled in October 2019 in order to provide basic inventory information and monitor an environmental flow (NSW DPIE/CEWO), and Torriganny Creek (close to Booligal) was also monitored in October 2019 for the same reasons.

In all areas, a minimum of three sites were sampled on each sampling occasion.

Fish Sampling Methods

Fish populations were sampled at all sites and on all sampling occasions using a combination of large and small fyke nets. These methods successfully capture fish of all body sizes and life stages in Australian inland waterways (Arthington et al., 2005; Balcombe et al., 2007). Large double-winged fyke nets with a 13 mm stretched mesh and 8 m wings (1 m deep) were set parallel to the bank with their openings facing in opposite directions upstream and downstream from a central post. Cod-ends were secured above the water surface in order to allow air-breathing vertebrates to survive if they became entrapped. Small double-winged fyke nets with a stretched mesh of 2 mm and a wing width of 3 m (1 m deep) were set in an identical manner. All fyke nets were set in the afternoon (as close as possible to 4.00 pm) and retrieved the following morning (as close as possible to 9.00 am). Following the clearing of fyke nets, all fish were held in shaded water-filled buckets prior to processing.

Figure 2. Habitats sampled between 2017 and 2020 ranged from areas of open water in the Lake Cargelligo system (top) to channelised riverine environments such as Booberoi Creek (bottom) (Photos: Adam Kerezsy).

Fish species were identified using a combination of published literature relating to fishes of the Murray-Darling Basin (Allen et al., 2002; Lintermans, 2007). All sampled fish were measured from the tip of the snout to the caudal peduncle to obtain a standard length (SL) measurement in millimetres. Following identification and measurement for standard length, all native fish were returned to the water alive and alien species were euthanised using a dilute solution of Aqui-S (as per OEH Animal Research Authority AEC Approval No. 171017/01).

Data Presentation and Comparison with Previous Studies

Owing to the large number of sites and the fact that some sites were sampled on multiple occasions whereas others were only sampled once over the extended seasonal sampling timeframe, analysis of the entire dataset was neither envisaged nor attempted.

Overall total catches were calculated and tabulated for each site and species. Totals were calculated by adding all results from all sampling events in a particular area, with the number of sampling occasions also noted.

Totals were used in areas sampled multiple times (Lake Cargelligo and Booberoi Creek) in order to graph and compare fish community composition and provide a visual representation of the contribution of common and alien species in such areas.

Fish species' presence/absence was compared to previous sampling data within the Lachlan catchment (Llewellyn, 1983; Harris & Gehrke, 1997; Growns, 2001; Kerezsy, 2005; MDBC, 2004a; Davies et al., 2008; Price, 2009; Davies et al., 2012) in order to permit discussion of the current state of fish communities within the mid-Lachlan catchment.

Results

Total Fish Results, 2017–2020

Close to 30,000 individual fish were sampled at all sites in the mid-Lachlan between 2017 and 2020, with the vast majority (84%) being native species (Table 1). Small gudgeons of the genus *Hypseleotris* were the most commonly sampled species and were found at all sites except in the main channel of the Lachlan (Table 1). Bony herring (*Nematolosa erebi*) were also sampled in large numbers (>10,000; Table 1); however, their range was generally concentrated in the open water habitats (such as Lake Cargelligo and the Brewster Weir pool; Table 1).

Small-bodied native species such as un-specked hardyhead (*Craterocephalus stercusmuscarum fulvus*), Australian smelt (*Retropinna semoni*) and flathead gudgeon (*Philypnodon grandiceps*) were sampled in reasonable numbers; however, they were generally detected more often in Lake Cargelligo and Booberoi Creek, the two areas that were sampled on multiple occasions.

Large-bodied native species such as yellowbelly and Murray cod were sampled in small numbers, and only from Lake Cargelligo, and the endangered population of olive perchlet was detected within its known range in the Brewster Weir pool (Figure 1; Table 1).

Freshwater catfish – classified as a listed endangered population within the M-DB – was found at four locations, including Booberoi Creek, Mountain Creek, Wallamundry Creek and Lake Cargelligo. At each location, one adult catfish was sampled (Figure 1; Table 1).

The most commonly sampled alien species was gambusia (*Gambusia holbrooki*), which was present at all sites except the main channel of the Lachlan River and Yarrabandai Creek (Figure 1; Table 1). Carp were similarly distributed, occurring at all sites except Wallamundry Creek. Goldfish and redfin were sampled in far lower numbers and at a more limited number of sites (Table 1).

Fish Communities in Different Areas

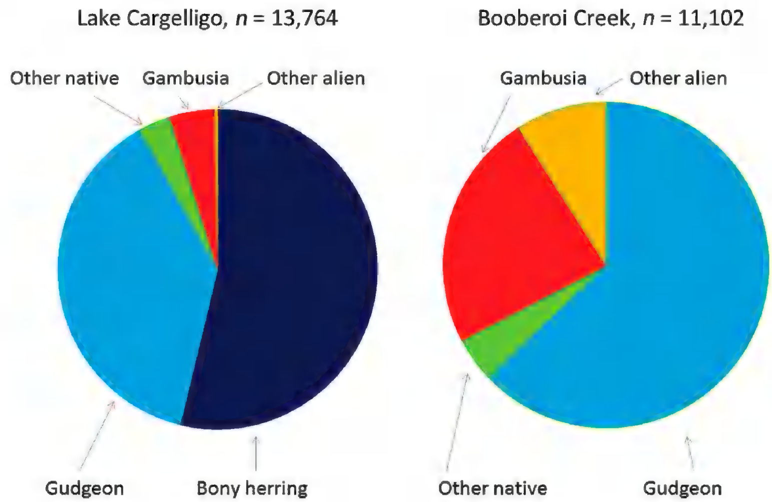
The fish community in the meandering and riverine Booberoi Creek (summed from eight sampling occasions) was dominated by small species such as gudgeons and gambusia, whereas the open-water habitat of Lake Cargelligo was dominated by bony herring (Figure 3).

In Booberoi Creek, gudgeons and gambusia were sampled during all surveys (eight) and carp were sampled during seven. Goldfish were sampled during five surveys, and un-specked hardyhead and flathead gudgeon during four. All other species in Booberoi Creek (bony herring, freshwater catfish, Australian smelt and redfin) were sampled during one survey.

Table 1. Total numbers of fish sampled at sites throughout the mid-Lachlan catchment from 2017–2020, including number of times each site was sampled.

Scientific name	**Common name**	**Booberoi Creek** (sampled eight times)	**Lake Cargelligo** (sampled seven times)	**Brewster Weir Pool** (sampled three times)	**Mountain Creek** (sampled once)	**Wallamundry Creek** (sampled once)	**Yarrabandai Creek** (sampled once)	**Torriganny Creek** (sampled once)	**Lachlan main channel** (sampled once)	**Totals**
Native species										
Nematolosa erebi	Bony herring	7	7400	1690	1569	—	—	—	—	**10666**
Retropinna semoni	Australian smelt	79	131	—	—	3	—	—	—	**213**
Tandanus tandanus	Freshwater catfish	1	1	—	1	1	—	—	—	**4**
Craterocephalus stercusmuscarum fulvus	Un-specked hardyhead	140	52	1	—	—	—	—	—	**193**
Ambassis agassizii	Olive perchlet	—	—	11	—	—	—	—	—	**11**
Macquaria ambigua	Yellowbelly	—	18	—	—	—	—	—	1	**19**
Maccullochella peelii peelii	Murray cod	—	3	—	—	—	—	—	—	**3**
Philypnodon grandiceps	Flathead gudgeon	269	245	12	—	—	—	—	—	**526**
Hypseleotris spp.	Carp gudgeons	6981	5242	712	97	25	149	25	—	**13231**
Alien species										
Cyprinus carpio	Carp	976	22	6	73	—	17	13	3	**1110**
Carassius auratus	Goldfish	28	1	—	—	—	1	2	5	**37**
Gambusia holbrooki	Gambusia	2620	631	259	89	6	—	125	—	**3730**
Perca fluviatilis	Redfin	1	18	—	—	—	—	—	—	**19**

Figure 3. Proportional representation of summed totals of all fish sampled in Lake Cargelligo (left) and Booberoi Creek (right) between 2017 and 2020.



In Lake Cargelligo, gudgeons and bony herring were sampled during all surveys (seven), carp and gambusia during six, flathead gudgeon during five, and yellowbelly, redfin and Australian smelt during four. Un-specked hardyhead were sampled during three surveys, Murray cod during two, and both freshwater catfish and goldfish were sampled during one survey.

The population of native fish sampled in Booberoi Creek represented 67% of the total, whereas in Lake Cargelligo native fish comprised 95% of the total.

Comparison with Existing Surveys in the Lachlan Catchment

Two native species (yellowbelly and *Hypseleotris* gudgeons) and three alien species (carp, goldfish and gambusia) have been detected during nine surveys in the mid-Lachlan since 1983 (Tables 1 & 2).

Two native species (bony herring and flathead gudgeon) have been detected during eight of the nine surveys, and two native species (Murray cod and Australian smelt) and one alien species (redfin) have been detected during seven (Tables 1 & 2). Native species detected in fewer surveys include un-specked hardyhead (five surveys), freshwater catfish (four surveys), silver perch (three surveys) and olive perchlet (two surveys; Tables 1 & 2). Southern pygmy perch, flathead galaxias, Murray-Darling rainbowfish, southern purple-spotted gudgeon and trout cod have not been detected by any of the surveys of freshwater fish in the mid-Lachlan (Tables 1 & 2).

Discussion

Fish Records for Unknown or Poorly Known Areas Can Inform Management

River and catchment management relies on accurate records such that decisions can be made in relation to restoration works or the provision of flows that may have ecological benefit. During the monitoring studies presented here, both NSW DPIE and CEWO have used the fish survey results from specific areas to inform the timing and volume of environmental flows (J. Lenehan, DPIE, pers. comm.).

Following the detection of endangered freshwater catfish in Booberoi Creek, environmental flows were directed down this off-river system, and during subsequent sampling events populations of small native species such as un-specked hardyhead and flathead gudgeon were also recorded (Table 1). Subsequent sampling of other off-river creeks such as Wallamundry and Mountain Creeks also found catfish present and may become target areas for future environmental flows (J. Lenehan, NSW DPIE, pers. comm.).

TTable 2. Records of fish species in the mid-Lachlan catchment during surveys undertaken since 1983. Empty squares indicate absence.

Family	Scientific name	Common name	Llewellyn	Harris & Gehrke	Growns	MDBC SRA Pilot Study	Kerezsy	SRA 1 Davies et al.	MDFRC Price	SRA 2 Davies et al.	Recent surveys
			1983	1997	2001	2004	2005	2008	2009	2012	2017–1920
Native species											
Clupeidae	*Nematolosa erebi*	Bony herring		*	*	*	*	*	*	*	*
Retropinnidae	*Retropinna semoni*	Australian smelt	*	*	*	*	*	*			*
Plotosidae	*Tandanus tandanus*	Freshwater catfish	*		*		*				*
Atherinidae	*Craterocephalus stercusmuscarum fulvus*	Un-specked hardyhead	*				*	*	*		*
Ambassidae	*Ambassis agassizii*	Olive perchlet	*								*
Percichthyidae	*Macquaria ambigua*	Yellowbelly	*	*	*	*	*	*	*	*	*
Percichthyidae	*Maccullochella peelii peelii*	Murray cod	*		*	*		*	*	*	*
Terapontidae	*Bidyanus bidyanus*	Silver perch	*	*			*				
Eleotridae	*Philypnodon grandiceps*	Flathead gudgeon	*	*	*	*	*		*	*	*
Eleotridae	*Hypseleotris* spp.	Carp gudgeons	*	*	*	*	*	*	*	*	*
Alien species											
Cyprinidae	*Cyprinus carpio*	Carp	*	*	*	*	*	*	*	*	*
Cyprinidae	*Carassius auratus*	Goldfish	*	*	*	*	*	*	*	*	*
Poecilidae	*Gambusia holbrooki*	Gambusia	*	*	*	*	*	*	*	*	*
Percidae	*Perca fluviatilis*	Redfin	*	*	*	*	*			*	*

In Lake Cargelligo, the presence of most expected species in the Robinson Crusoe Island area similarly prompted the managers of this reserve (Cargelligo Wetlands and Lakes Council) to ask the water provider (WaterNSW) to consider altering their traditional management of the lake as a storage to also factor in the ecological and social benefits of more regular water delivery (P. Skipworth, CWLC, pers. comm.). The result has been that some water that normally would have flowed down the Lachlan has been diverted through the Lake Cargelligo system, and this appears to have had a positive effect on aquatic fauna (Tables 1 & 2).

In both of these cases, locally sponsored monitoring provided survey results that have then been used by managers to make informed decisions regarding catchment management.

The Biological Relevance of Repeated Sampling in Off-river Habitats

Broad-scale river surveys provide a snapshot of fish community composition in a catchment but are generally restricted to main channel sites, as opposed to lotic or lentic sites that are situated in creeks, lakes and floodplains (Davies et al., 2008; Davies et al., 2012; Price, 2009). Localised sampling has the potential to fill knowledge gaps with regard to catchment fish communities by augmenting broad-scale surveys with monitoring in a wider range of off-river habitat types. Furthermore, the repeated nature of some of this sampling (for example in Booberoi Creek and Lake Cargelligo) may deliver more informative and useful fish community data from which to inform river and water management.

Results from the mid-Lachlan between 2017 and 2020 compare favourably with all previous surveys with regard to species present (Table 2) and suggest that these off-river areas may provide valuable habitat and ecosystem services, particularly as potential refuge or nursery areas (Datry et al., 2017).

The Lake Cargelligo system (Figures 1 & 2) was essentially altered from an ephemeral wetland to a permanent storage from the early 1900s (Kerezsy, 2005). This has created large areas of shallow, open water and provided ideal habitat for pelagic schooling species such as bony herring, Australian smelt and un-specked hardyhead. The numerical dominance of bony herring in this habitat is exemplified by the survey results from 2017 onwards (Table 1), and unsurprisingly, the species also favours the similar lacustrine environment created by the Brewster Weir (Table 1).

In contrast, in the channelised and riverine habitat that occurs in Booberoi Creek (Figure 2), bony herring are uncommon and the community is dominated by small generalists such as gudgeons (*Hypseleotris* spp.) and alien gambusia (Table 1).

Carp are generally present in off-river habitats of the mid-Lachlan. However, it is notable that commercial carp fishers have been operating in Lake Cargelligo since 1 May 2018 and estimate they have removed approximately 180 tonnes of carp from the system in the intervening period (Steve Hounsell, pers. comm). It is therefore possible that sustained carp removal may be contributing to the positive results for all native species recorded from Lake Cargelligo since mid-2018 (Table 1).

Monitoring undertaken in the mid-Lachlan between 2017 and 2020 has confirmed the presence of endangered species such as freshwater catfish in four areas (Table 1) and has similarly confirmed the presence of olive perchlet within the Lake Brewster weir pool (Table 1) following the discovery of this isolated population approximately 10 years earlier (McNeill et al., 2008).

However, five species remain elusive in the mid-Lachlan, despite predictions that they were historically present and may still occur (Davies et al., 2008; Davies et al., 2012). Flathead galaxias (*Galaxias rostratus*), Murray-Darling rainbowfish (*Melanotaenia fluviatilis*), trout cod (*Maccullochella macquariensis*), southern pygmy perch (*Nannoperca australis*) and southern purple-spotted gudgeon (*Mogurnda adspersa*) have not been recorded in mid-Lachlan surveys since 1983 (Table 2), and museum records do not exist for any of these species except for a single record of a rainbowfish from Hillston in 1950 (Amanda Hay, Australian Museum, pers. comm.).

The Longevity and Flexibility Associated with Localised Monitoring Projects

Localised and locally supported fish sampling can be timed to coincide with and/or inform environmental watering events, and can be tailored and expanded to meet desired project management goals where necessary. For example, all of the

sampling that has occurred in Booberoi Creek has been targeted with a view to obtaining before, during and after samples of fish populations relative to the timing and volume of environmental water deliveries (J. Lenehan, DPIE, pers. comm.), and the sampling in Wallamundry Creek was initiated for the same reason. It is envisaged that long-term monitoring of Booberoi Creek is likely to continue (J. Lenehan, NSW DPIE, pers. comm.), and commencing in late 2020, another project aimed at mid-Lachlan creeks in the Forbes/Condobolin area is also planned (Mary Ewing, Lachlan Valley Water, pers. comm.).

In Lake Cargelligo, the local not-for-profit Cargelligo Wetlands and Lakes Council made a decision to continue fish monitoring in the Robinson Crusoe Island reserve area on a regular basis from 2019–2020 onwards. This decision was based on the early fish survey results and the need to create a longer-term dataset upon which to base environmental watering management plans (P. Skipworth, CWLC, pers. comm.).

This flexible approach to sampling and monitoring can have unintended benefits, with a good example being the detection of freshwater catfish in Mountain Creek (Table 1), which was initially sampled (along with the Brewster weir pool) for the purposes of auditing the Lachlan population of the endangered olive perchlet.

Locally sponsored sampling can complement established long-term monitoring projects (Dyer et al., 2019) by expanding the overall sampling area within a catchment and focusing on specific habitats or areas that are beyond the scope of larger projects.

Involvement, Interest and Education of Local Participants

Monitoring that is sponsored and supported by community and/or stakeholder groups – by its very nature – encourages the participation of local communities, and in the mid-Lachlan numerous examples relating to the work that has been carried out between 2017 and 2020 suggest that the flow-on effects regarding community engagement are beneficial.

During two of the Booberoi Creek monitoring events (spring 2018 and spring 2019), fish sampling took place as part of stakeholder engagement weekends/overnight trips that included local landholders, representatives from the local Aboriginal community and government agents (from NSW DPIE and CEWO). The majority of participants – but most notably the landowners – expressed interest (and surprise) at both the variety and abundance of small-bodied native fish, and most commented that although they had lived adjacent to the creek for extended periods, they were somewhat ignorant of (but keen to learn about) the local biodiversity (landowners D. Stewart, J. Ireland, pers. comms).

In April 2019, as part of routine sampling of the Robinson Crusoe Island area sponsored by Cargelligo Wetlands and Lakes Council, two coordinators and six Aboriginal teenagers from the Down The Track youth-at-risk program attended and assisted with both fish sampling and bird counts, as well as staying overnight and helping with general chores associated with bush camping (Figure 4). Coordinator Lana Masterson commented that the participants were all completely engaged with the activities, and – as soon as they were heading back to the 'mainland' by boat – enquired as to when they would be repeating the exercise (L. Masterson, Down The Track, pers. comm.).

Similarly, interest in ecological projects and associated work has become an accepted and possible career/occupation pathway for school-aged students, with one Year 10 student working on fish sampling within Lake Cargelligo as part of the local 'School to Work' work experience program (T. Kendall, careers advisor, Lake Cargelligo Central School, pers. comm.).

The Creation of New Projects Following Initial Engagement

Fish monitoring work undertaken in the mid-Lachlan from 2017 onwards has yielded some encouraging results regarding native fish, particularly for the areas that have been sampled on multiple occasions (Table 1; Figure 3). The communication of results from this work – mainly through informal networks and word of mouth – appears to have had a positive influence within the catchment, and as a consequence, monitoring of other areas, sponsored by different stakeholders, has commenced or will be commencing from 2020.

Figure 4. Members of the Down The Track program for at-risk youth participating in fish sampling at Robinson Crusoe Island, Lake Cargelligo, in March 2020 (Photo: Mal Carnegie).

From mid-2020, the ongoing monitoring of the Robinson Crusoe Island area within Lake Cargelligo will be funded and supported by a partnership between Cargelligo Lakes and Wetlands Council (a local not-for-profit group) and Lachlan Shire Council (P. Skipworth, CWLC, pers. comm.). This is an important development as it indicates that local governments have the ability to contribute positively to community-based projects that have a broad utilitarian goal (i.e. better management of the catchment for the benefit of all parties).

Commencing in spring 2020, a three-year project will commence in the Belubula catchment, and this work will be supported by Newcrest Mining (T. Thornberry, Newcrest, pers. comm.). The Belubula, which rises in high country between Bathurst and Orange and joins the Lachlan close to Gooloogong, can be considered an upstream tributary of the Lachlan, as opposed to the majority of sites discussed and sampled to date (Table 2). However, the Belubula is also poorly known regarding fish communities; thus, there is demonstrated interest from local landholders and government agencies (G. Fitzhardinge, M. Martin, C. Dunhill, J. Sanders, M. Payten, C. Proctor, pers. comms), and the results from these surveys are also likely to contribute to management of both the Belubula and Lachlan Rivers.

In a similar fashion, Lachlan Valley Water – a water users group with a focus on irrigation – will sponsor the aforementioned fish monitoring in another poorly known area of the Lachlan (from Jemalong, downstream of Forbes, to Wallamundry, in the vicinity of Condobolin) commencing in spring 2020.

Lastly, based on the success of the community-based monitoring workshops held at Booberoi Creek (spring 2018 and spring 2019), NSW DPIE is planning to repeat this model (incorporating fish sampling, bird sampling and other ecological information) in the lowland section of the Lachlan in the area close to Booligal, again commencing in spring 2020 (J. Lenehan, NSW DPIE, pers. comm.).

Conclusions

Monitoring specific or targeted areas within a catchment is beset by the same problems that apply to broad-scale monitoring, because not all areas are likely to be sampled, and some important areas will inevitably be missed. However, if this monitoring is supported by a broad range of local and regional groups – as the surveys presented and discussed here have been – the chances of obtaining accurate information that can guide catchment management can certainly be improved.

Contrary to the results from broad-scale riverine surveys (Davies et al., 2008; Price, 2009; Davies et al., 2012), the results from specific areas within the mid-Lachlan (for example Booberoi Creek and Lake Cargelligo) indicate that off-river areas are likely to provide habitat for the majority of extant native species. The importance of these habitats can be confirmed by targeted fish surveys, especially if sampling is carried out on multiple occasions. Replicating surveys such as those documented herein, both within individual catchments and across the M-DB, would undoubtedly provide enhanced records and reliable information upon which fishery and catchment managers can base decisions.

Though desirable, monitoring at these scales is beyond the capacity of state agencies and the MDBA. However, the work cited demonstrates that there is both capacity and intent within local riverine communities to learn about and improve river management with a view to enhancing biodiversity and overall catchment health. The diversity of interested community and stakeholder groups – encompassing a local not-for-profit, a local council, a mining company, an irrigation group, Indigenous owners, and state and federal agencies charged with delivering environmental flows – is indicative, perhaps, of a changing mood within riverine communities in the M-DB, and bodes well for the future.

A bottom-up approach to catchment management, where local and regional people can invest in monitoring programs that seek to document the biota and health of their rivers and waterways, could be an extremely effective way of sharing the considerable load associated with making informed management decisions. The template that has evolved – and is evolving – in the Lachlan catchment in New South Wales could easily be adapted and replicated in other catchments across the M-DB and elsewhere.

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Productivity and Biomass of Australia's Rangelands: Towards a National Database

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Abstract

This paper reviews information about field observations of vegetation productivity in Australia's rangeland systems and identifies the need to establish a national initiative to collect net primary productivity (NPP) and biomass data for rangeland pastures. Productivity data are needed for vegetation and carbon model parameterisation, calibration and validation. Several methods can be used to estimate pasture productivity at various spatial and temporal scales, ranging from *in situ* measurements to satellite-based approaches and biogeochemical modelling. However, there is a barrier to implementing national vegetation and carbon modelling schemes because of the lack of digitised and readily available data derived from field observations, not because of the lack of modelling expertise. Our main goal in this paper is to explore the potential for consolidation of existing NPP and biomass databases for Australian rangelands. A protocol structure was proposed to establish a productivity database for Australia. The TERN (Terrestrial Ecosystems Research Network) national field data network for rangeland pasture productivity monitoring and modelling team could potentially coordinate the database. Government agencies and national and international research institutions could use the outputs from productivity models to inform greenhouse gas emissions and in measuring mitigation activities relevant for reporting against the United Nations' Sustainable Development Goals and other international obligations. Other applications include monitoring fire danger, tracking ecological restoration and protection, and estimating fodder availability. Australian researchers have the tools needed to succeed in creating such a national database and a robust community of practice to curate it, enhance it and benefit from its availability.

Keywords: arid/semi-arid rangelands, biophysical models, land management, productivity database, rangeland monitoring and management, vegetation and carbon modelling

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Introduction

Most of the Australian continent (≈75%) is covered by rangeland systems composed of savannas, woodlands, shrublands and native and non-native grasslands (Bastin et al., 2009). Here, we adopt the broad rangeland system definition that includes any of the biomes mentioned. Non-forest vegetation covers over 70% of the vegetated land surface and represents about half of Earth's terrestrial productivity. However, non-forest vegetation contributes less than 20% of global biomass (Pan et al., 2011). Compared to forest systems that account for 80% of Earth's total plant biomass (Kindermann et al., 2008), the collection of non-forest data for model calibration and validation, such as rangelands, has received less attention. Only approximately a tenth of Australia's carbon is stored in forests, while about two-thirds is held in Australia's arid and semi-arid biomes, of which two-thirds is stored below ground (Donohue et al., 2012; Poulter et al., 2014).

The Terrestrial Ecosystems Research Network (TERN, https://www.tern.org.au/) Surveillance Project uses a spatially extensive network to monitor more than 600 sites distributed through the country along environmental gradients and key biomes. TERN is Australia's land ecosystem observatory, which measures and records terrestrial ecosystem attributes and condition over time, from continental scale to field sites, at hundreds of representative locations (TERN, 2020). Data collected by TERN are standardised, integrated and converted to model-ready data that enable users to track and interpret changes in land ecosystems. However, not all TERN programs collect vegetation productivity or biomass data (e.g. TERN SuperSites). Rangeland net primary production has been measured once at about 180 sites and documented in the Biomass Plot Library (http://www.auscover.org.au/datasets/biomass-plot-library/), a TERN AusCover initiative that created an inventory of above-ground biomass data for model calibration and validation.

A study by Roxburgh et al. (2004) concluded that "... current empirical database on growth and carbon dynamics in arid Australia is insufficient to satisfactorily calibrate or validate current continental-scale models, and that more empirical work in Australian arid ecosystems is urgently required ...". Since then, a significant amount of data has been collected, such as the resources available in the TERN network, in addition to data that are not widely available to researchers. Despite this, the problem identified by Roxburgh et al. (2004) remains relevant today. From a modeller's perspective, consistent biomass data from rangeland systems are under-represented in most available data collections. There is no empirical database in Australia with coverage across diverse biomes to validate national-scale productivity models. The lack of a consistent database leads, amongst other things, to great variability in model estimates. In a model intercomparison study, this variability has ranged fivefold from 0.67 to 3.31 Gt C per year (Roxburgh et al., 2004). More recently, Haverd et al. (2013a) found some model discrepancies in the arid biomes and larger discrepancies in temperate regions (see Figure 17 in Haverd et al., 2013a).

A well-curated productivity database would assist in modelling practices. The outputs from productivity models are used for specific policy or management initiatives in Australia, e.g. the Australian Government's Joint Agency Drought Taskforce (https://www.pmc.gov.au/domestic-policy/joint-agency-drought-taskforce/) for reporting GHG emissions and measuring mitigation activities that are relevant for reporting against the United Nations Sustainable Development Goals (SDG) and the National Determined Commitments of the Paris Agreement (Griggs et al., 2014; United Nations, 2015). The assessment of sustainable livestock densities and tracking changes in the long-term productivity of rangelands helps to measure progress against SDG No. 12: "responsible consumption and production". Field observations of vegetation structure and biomass have helped determine the proportions and distributions of C_3 and C_4 grasses in Australia (Hattersley, 1983). A rangeland productivity database is critical for generating robust and properly calibrated model outputs. In addition to empirical and quantitative modelling approaches, productivity model outputs can be used for technological applications in computing science, such as artificial intelligence and machine learning (Musib et al., 2017). This field of science is rapidly evolving, and site-based training data in particular are the currency. In machine learning, data are used for model calibration, validation, and to adjust internal algorithms.

One of the objectives of the work reported in

this paper was to develop a protocol structure for an Australian rangeland productivity database. We focus on the amount of relevant existing data that has not been curated for public release. There is only a limited amount of time to make this data available as the custodians of the data move to other projects or retire.

In the following sections, we describe the spectrum of users of field observations and the applications of the end-products. We review the literature and list rangeland field observations in which NPP and biomass have been directly or indirectly measured in Australia.

Data and Data Users

The range of users of the rangeland database includes researchers, land managers and government. The researchers group encompasses a broad diversity of users, from those working with vegetation productivity models to fire scientists and applied ecologists. This group uses field data to derive model parameters and validate predictions and projections at various temporal and spatial scales. Model outputs contribute to assessments, from the paddock to national and global levels. The land managers group includes primary producers and those who provide advice to producers (e.g. agri-businesses, extension officers, NRM groups). Land managers can make use of the field observations by incorporating them into management decisions and practices, especially when the information is provided to them in processed form, often as part of broader information packages. Local state, territory and national governments use field observations to build their assessment and accounting systems, which are used to provide information to land managers, develop education and extension materials, support policies and meet national and international reporting obligations. On the latter, such reporting systems are heavily calibrated with observations. These are used to report annual carbon emissions and sinks from the land sector to the United Nations Framework Convention on Climate Change (UNFCC), and towards the 2030 SDG.

Governments and institutions use the outputs and recommendations from land managers and researchers in broader decision-making processes. Government agencies need to report, for example, carbon emissions at the national scale, fire danger and environmental conditions (e.g. State of the Environment). The outputs of productivity models help to estimate fodder availability at regional scales and yield projections for drought declaration, monitoring and relief (Nelson et al., 2010). These outputs help government agencies and institutions to engage with the public, inform policy recommendations, and report against international treaties and other obligations such as the Global Primary Production Data Initiative (GPPDI), the NPP Multi-Biome datasets (Olson et al., 2001), UNFCC and SDG.

The interest in modelling productivity of rangeland systems has two main drivers: economic and environmental. The contribution of the agricultural industry (crops and livestock) to the Australian economy was about AU$60 billion in 2018 (ABARES, 2018), which ranked above the 10-year average despite the drought conditions, and it contributes about 3% to the Australian gross domestic product. The contribution to the Australian economy from rangelands is estimated at about AU$5 billion per year (Foran et al., 2019). The main overseas markets for agricultural products that depend on production in rangeland systems are China, Japan, the USA, the European Union, Indonesia and the Republic of Korea (ABARES, 2018). Monitoring of rangelands is also required for carbon accounting (Metcalfe, 2014), to understand species distributions (Harris et al., 2013) and soil health, e.g. via the Australian DustWatch Program (Leys et al., 2020).

Different types of modelling have varying data intensity requirements. For example, the C-Store system (Donohue & Renzullo, 2015) is an Australian remote-sensing and observation-driven carbon assessment modelling platform that assesses rangeland productivity at the national scale at a relatively fine spatial resolution. The C-Store system is data driven, especially using remotely sensed data, and accounts for temporal dynamics of vegetation. C-Store can also produce estimates of model uncertainty. Maximum model simplicity and computational efficiency were essential criteria in the development of the C-Store system. The vegetation monitoring capacity of C-Store is calibrated to field observations. Higher numbers of observations across Australia have a positive impact on model accuracy and in reducing uncertainty.

The Pastures from Space (www.pasturesfromspace.csiro.au) model (Mata et al., 2004) assumes that land managers would benefit from better information on which to base production decisions. It also assumes that sustainable production may not be achieved because of the lack of information to make sound management decisions on feed resources. Pastures from Space uses remotely sensed data to provide estimates of pasture production during the growing season (Hill et al., 2004; Edirisinghe et al., 2011; Smith et al., 2011). In recent years, farmers have accounted for about 70% of total users logging into the Commonwealth Scientific and Industrial Research Organisation (CSIRO)'s systems seeking estimates of pasture biomass and growth rates. One limitation of Pastures from Space is that it has little overlap with rangeland systems. Pastures from Space covers a portion of rangeland in New South Wales (NSW), but none in South Australia, Western Australia, the Northern Territory or Queensland. The main outputs of the model are pasture biomass, or feed on offer, and pasture growth rate estimates. Field observations are used to calibrate the model and validate its outputs. The Pastures from Space model has not been updated since November 2018, and as a result, producers are unable to access up-to-date data. The Pastures from Space program could be improved and updated by accessing the type of database proposed in this article.

A Dynamic Global Vegetation Model (DGVM) and land surface models can simulate shifts in potential vegetation, and its associated biogeochemical and hydrological cycles, as a response to changes in climate. DGVMs generally combine biogeochemistry, biogeography, and disturbance sub-models (e.g. wildfire) and are able to simulate carbon, water and energy exchanges between the land surface and the atmosphere. DGVMs generate outputs at sub-diurnal to century time scales (Arora, 2002; Pitman, 2003). The state and trend of carbon, water and nutrient pools are determined by modelling the flows of energy and materials between them in response to weather and a variety of natural and human disturbances (Cramer et al., 2001). Vegetation is typically classified into plant functional types, which differ in their physiological and phenological attributes (Reick et al., 2013). Depending on their sophistication, DVGMs represent a variety of natural (e.g. fire) and human disturbances (e.g. land-use change), and associated vegetation dynamics (Sitch et al., 2003; Haverd et al., 2018). In hindcast mode, i.e. modelling historical biomass, DGVMs such as the CABLE model (Haverd et al., 2018) use carbon pool data and vegetation field observations for model evaluation. They are also an essential component of the multiple constraints approach. This approach uses a suite of observations to minimise uncertainty in model performance through formal parameter estimation (Raupach et al., 2005). Biomass data are not the most constraining in this context because of spatial and methodological variations, and the inclusion of multiple observation types mitigates bias from any single type. The pattern of biases varies regionally and through time and can help identify structural issues that relate to un-modelled or poorly modelled processes (Haverd et al., 2013a).

For Australia, field observations of biomass, leaf NPP (as litterfall) and soil carbon (Raison et al., 2003; Barrett, 2013) were combined into a DGVM with stream flow and Eddy covariance flux measurements to produce estimates of continental productivity (Monteith & Unsworth, 2013). The outputs showed significantly smaller uncertainties at regional scales than previous estimates (Haverd et al., 2013a). These results were incorporated in the first comprehensive Australian carbon budget (Haverd et al., 2013b). The model is driven by remotely sensed vegetation, and biomass field observations were used to validate hindcast results and reduce model uncertainty.

Fire scientists and ecologists are also interested in rangeland and pasture data. For example, fire danger in rangelands is driven by intermittent periods of biomass availability following significant precipitation events or long-term climate oscillations (Greenville et al., 2009). Understanding standing biomass, and the rangeland's responsiveness to precipitation, is important to assess accurately fire risk and fire-related carbon emissions. In applied ecology, for example, Gould et al. (2015) used field observations to validate a vegetation index derived from remotely sensed data, subsequently used to identify potential wildlife refuges. Once the vegetation index was validated with the field observations, it was possible to develop a method for finding areas likely to function as refuges against

drought and climate change. Gould et al. (2015)'s method assumes that locations where vegetation productivity is high and stable during drought may act as refuges. Such locations are likely to provide a more reliable supply of habitat resources for a wide range of species. Gould et al. (2015) found a stronger relationship between satellite data and field observations of vegetation biomass and productivity in white gum (*Eucalyptus* sp.) woodland than kangaroo grass (*Themeda triandra*) communities. The method referred to above has been tested in the Australian Tasmanian Midlands. In another ecological example, researchers used field observations and satellite data to monitor the negative impact of feral horses (Driscoll et al., 2019) on native grasslands in the Australian Alps (Porfirio et al., 2017).

Several applications have been developed to improve farming practices, which connect information at the farm level to a broader system managed by agronomists or researchers. For example, the AgWorld platform (https://www.agworld.com/au/) allows users to collect data at every level of their operation and enables them to freely share the data. The BackPaddock® application (Back Paddock Company, 2020) is similar to AgWorld, except that producers can keep track of soil test results. The Drought Feed Calculator app, developed by the New South Wales Department of Primary Industries, can be used by producers to calculate the best feed ration. The start-up Digital Agriculture Services (https://digitalagricultureservices.com/) provides rural data and analytics services to better predict and manage agriculture investment and commerce. There is a growing number of Enterprise Resource Planning packages used by producers that provide supply chain monitoring and certification against industry-led metrics.

Existing Rangeland Productivity Observations in Australia

In this section, we describe several existing databases that contain field observations of rangeland productivity in Australia (Table 1). The description includes the name of each dataset, together with basic information about a selection of datasets that are publicly available. We acknowledge that this list is not complete, but it provides an overview of the different groups in Australia interested in collecting this type of information, and the context in which the data are used. There are several methods that can be used to measure ground cover, biomass and composition, and remote sensing is a rapidly expanding area. This includes both satellite information and local equipment such as ground-based LIDAR that generate large volumes of point cloud data. When these new datasets merge with traditional physical measures, they can generate a rich volume of data with different granularities. However, how these datasets merge together is critical, and if they seat in silos and therefore are not properly connected, they cannot be fully utilised.

The Global Primary Production Data Initiative and the NPP Multi-Biome Dataset

The Global Primary Production Data Initiative (GPPDI) and the NPP Multi-Biome datasets (Olson et al., 2001) were established by the International Geosphere-Biosphere Programme (IGBP, http://www.igbp.net/) and compiled NPP observations across the world to improve the supply, management and use of the data and information needed to attain IGBP's scientific goals. The database covers 2500 sites and underwent an extensive review under the Ecosystem Model-Data Intercomparison (EMDI) process (Olson et al., 2011, 2013). This long-term program was used to improve worldwide modelled estimates of terrestrial NPP for different biomes (Prince et al., 2001; Zheng et al., 2003, 2004) and in the global EMDI project (Olson et al., 2011, 2013). The GPPDI dataset spans the period between 1931 and 1996, which unfortunately is not covered by most current satellite data widely used in NPP and biomass models at national and global scales. These field observations, however, can be used with data from the Landsat Satellite Missions (US Geological Survey, 2018) that cover a period from 1972 to date, or to validate and calibrate hindcast model runs. Although these datasets have very few points in Australia, the methods and protocols used to collect and combine the data could be used in the future to expand the dataset.

The GPPDI dataset is divided into three categories, namely: Class A representing intensively studied or well-documented study sites; Class B representing more extensive sites with less documentation and site-specific information available; and Class C representing regional collections of half-degree latitude-longitude grid cells. Class C

is less well documented compared with Class A and B, and it may be regarded as less reliable. The Australian continent is represented in the GPPDI dataset with fourteen Class A and seven Class B sites, comprised of C_3 and C_4 grasses, forests and shrublands.

The Nutrient Network Dataset

The Nutrient Network (NutNet, https://nutnet.org/) is hosted by the University of Minnesota and started collecting data in 2007. The NutNet project aims at quantifying human impacts on grassland systems at the global scale. The dataset covers more than 40 sites around the world. The specific goals of NutNet are to:

- collect data from a broad range of sites in a consistent manner to allow direct comparisons of environment-productivity-diversity relationships among systems around the world; and
- implement a cross-site experiment requiring only a nominal investment of time and resources by each investigator, but quantifying community and ecosystem responses in a wide range of herbaceous-dominated ecosystems (from desert grasslands to Arctic tundra).

Grassland ecologists around the world may become members of NutNet, but they are required to carefully follow research protocols for sampling. Australian grasslands are represented in the NutNet dataset by 13 sites (Morgan et al., 2016). The NutNet database has been used, for example, to investigate the relationship between plant productivity and species richness (e.g. Adler et al., 2011) and to study ecological interactions in grasslands (e.g. Seabloom et al., 2013; Ziter & MacDougall, 2013; Lind et al., 2017; Anderson et al., 2018).

NPP Multi-Biome: VAST Calibration Data

The NPP Multi-Biome: VAST Calibration Data provides observations from Australia for use in parameterising the Vegetation and Soil-carbon Transfer (VAST) Model (Barrett, 2002, 2013). The VAST dataset contains 588 individual sites across Australia, with estimates of above-ground NPP based on cut grass swards and visual assessment of growth, litterfall (leaf and fine twig), measurements of above-ground biomass (phytomass), fine litter mass, and measurements of soil carbon concentration and soil bulk density in surface layers (0–150 mm depth interval). These data were derived from 174 original literature references describing study sites throughout Australia. The data cover the period between 1965 and 1998, and sites used in VAST were in steady state, i.e. ecologically, in climax systems. The VAST model and dataset were used to estimate and calibrate carbon dynamics in native and human-modified environments in Australia (Porfirio et al., 2010).

Western Australian Rangeland Monitoring System

The Western Australian Rangeland Monitoring System (WARMS) is a set of about 1620 permanent sites in the pastoral rangelands of Western Australia, although it includes some sites on land that has been removed from grazing and added to the conservation estate (Watson et al., 2007). The system is designed to assess changes in the perennial component of the vegetation. In shrubland vegetation, a direct census technique is applied, while in grassland areas the frequency and species composition of the perennial understorey is measured. While perennial biomass is not directly measured in either grassland or shrubland sites, it could be estimated for some purposes. The benefit of using a dataset such as WARMS is that it has a clear site stratification protocol and sites across all the grazed rangelands of Western Australia ($\approx$892,000 km^2), and it is supported institutionally in the long term. Grassland sites are assessed every three years, with shrubland sites every five years. The system was installed over a number of years, with the full set of planned sites installed by 1999, noting that a small number of site modifications are necessary in each year due to infrastructure or other changes (Watson et al., 2007).

A feature of rangeland ecosystems is that they follow state-and-transition model dynamics, rather than a linear Clementsian (climax) succession model (Clements, 1936). Thus, it is important to consider large changes in the capacity of a site to produce biomass due to state change. Understanding the frequency and likelihood of such changes is necessary to model this. Watson and Novelly (2012) used the WARMS dataset to

identify transitions observed on 306 grassland sites and 919 shrubland sites between 1993 and 2010, and suggested that state change had occurred on 11% of grassland sites and 1% of shrubland sites.

Aussie GRASS: Australian Grassland and Rangeland Assessment by Spatial Simulation

The Aussie GRASS project was established in 1996 as a multi-agency collaborative project and involved eight Australian agencies[a] (Carter et al., 2000a,b; Dyer et al., 2001; Richards et al., 2001; Tupper et al., 2001). It was funded by Land & Water Australia, led by the Queensland Department of Natural Resources and Mines, and involved the CSIRO and all rangeland states and territories in Australia. Aussie GRASS is an open-access national rangeland model that monitors pasture growth and biomass during drought and other climatic conditions (Littleboy & McKeon, 1997; McKeon et al., 2004). Aussie GRASS is based on comprehensive datasets (Day et al., 1997; McKeon, 2010) and currently provides 2000 reports per month to landholders, researchers and government (Owens et al., 2019). The model GRASP was derived from measures of NPP, quality and composition using the SWIFTSYND methodology (Day & Philp, 1997) from several datasets including 89 sites in 47 localities, giving 179 site-by-year combinations with three to seven observations over the growing season at each site (Day et al., 1997). Many other SWIFTSYND and grazing trial datasets in theses and industry/government-funded projects have been used to calibrate GRASP, including several SWIFTSYND sites that have been continuously monitored since 1986 (Cobiac, 2006; McKeon, 2010; Whish, 2017; Cowley et al., 2019). The dataset used to calibrate GRASP parameters within the Aussie GRASS framework at every grid cell location across the northern and southern rangelands of Australia was based on satellite imagery and 'spider mapping' with over 220,000 visual estimates of pasture biomass across Queensland, and was verified with 1300 measurements of pasture biomass between January 1994 and August 1995 (Hassett et al., 2000). This initial Queensland dataset was augmented with a further 59,500 visual estimates of pasture biomass (and verified with pasture measurements) across the southern rangelands in New South Wales, South Australia and Western Australia (Richards et al., 2001), and 110,000 visual estimates across the northern rangelands of the Northern Territory and the Kimberley region of Western Australia (Hall et al., 2001).

The Aussie GRASS model is used to explore herbivore carrying capacity, land sustainability, drought alerts and land degradation, and has been used extensively by government in relation to drought. The Aussie GRASS model was developed in collaboration with stakeholders and clients over several workshops, with the objective of transferring technology and sharing validation methods (Stone et al., 2019). This national program delivers information to land care groups, land managers and executive government about key biophysical processes associated with pasture growth (degradation and recovery) at paddock, regional and national scales. National Oceanic and Atmospheric Administration satellite imagery (NOAA, US Department of Commerce, https://www.noaa.gov/satellites/) was used to complement the system, providing regular estimations of grassland and rangeland biomass and productivity. The estimations were modelled on a daily time-step but presented publicly on a monthly time-step. The project was also scoped to generate a grassland and rangeland productivity seasonal forecasting system in collaboration with the Australian Bureau of Meteorology (http://www.bom.gov.au/) and potentially a long-term forecast based on general circulation models in collaboration with the US Scripps Institution of Oceanography (https://scripps.ucsd.edu/) and the CSIRO.

The Aussie GRASS project also had a social component that was used to collect information and make users aware of the products and how to use them. Project staff, primary producers, agribusiness and government personnel participated in 25 workshops, each tailored based on the needs of the different regions, to create awareness of the project and obtain feedback on prototype products. Up-to-date products were made available on information systems operated

[a] The late Dr Barry White, National R&D Coordinator for Land & Water Australia, fostered collaboration across Australia on rangeland data and modelling as part of the Climate Variability in Agriculture Program (CVAP, http://lwa.gov.au/programs/climate-variability-agriculture-program).

by the Queensland Government via the Queensland Centre for Climate Applications, such as The Long Paddock (https://www.longpaddock.qld.gov.au/) and Aussie GRASS (https://www.longpaddock.qld.gov.au/aussiegrass/) websites. Issues arose from the participative workshops related to the accuracy of the products and the applicability of seasonal climate forecasting in some regions (Carter et al., 2000a,b; Dyer et al., 2001; Richards et al., 2001; Tupper et al., 2001). Most participants preferred to have access to a State map (at a coarser pixel resolution) and a site-specific map (at a finer pixel resolution). ERDAS LAN files were made available on the website, and they were customised to satisfy the needs of individual clients. Other feedback related to cartographic adjustments, which were required to improve map readability.

Australian Fuel Biomass

Samples of litter and grass fuels were collected from 133 sites across Australia for studying continental patterns of landscape fire activity, severity and fuel consumption (Prior et al., 2017), which included rangeland and forest sites. Samples from the 133 sites were oven-dried and weighed to estimate moisture content and to convert field-fresh weights of fuel biomass to dry matter weight. The data are publicly available via an online repository (Prior et al., 2017). Murphy et al. (2019) used these data to estimate biomass consumption during fires in Australia and concluded that fire management on fire-prone tropical Australian savannas could be implemented to reduce carbon loss and emissions, but that care should be taken to avoid establishing a grass-fire cycle (Bowman et al., 2007) which could significantly increase emissions. Other examples of (unconsolidated) data collected for fire modelling studies, and independent from Prior et al. (2017)'s work, are:

- A dataset collected for a program of the Bushfire Cooperative Research Centre.
- The Victorian Forest Monitoring Program.
- A dataset collected in old-growth *Eucalyptus regnans* forest (datasets 1–3 are described in Volkova et al., 2018).
- Fuel consultations across the northern savanna (Bowman et al., 2007).
- Grass biomass data from 160 plots in northern Australia (Bowman & Prior, 2004).
- A consultation of C_3 and C_4 grasses across different Australian biomes (Murphy & Bowman, 2009).

None of the above datasets has been consolidated.

The Australian Carbon Database v1.0

The Australian carbon database v1.0 (Lawson & Donohue, 2015) is based on a literature search that found a total of 621 observations from 157 sites across Australian rangeland systems. This database describes 15 specific carbon pools, such as above-ground tree biomass, grass leaf biomass and soil carbon biomass, with only 16 observations being accompanied by error estimates, and with only 15 sites having repeated measures of any kind. The median footprint of the observations is about 0.5 ha. Key features of this database are:

- Includes biomass (plant material, either live or dead) and soil carbon stores (both above-ground and below-ground carbon).
- Compiles error estimates and other metadata related to data reliability.
- Discriminates between specific types or pools of carbon (e.g. leaves, stems, roots, litter) and between trees and grasses.
- Values are reported on a per-ground-area basis, as opposed to an individual plant basis.

The database is publicly available, but it has not been uploaded to a public repository.

Pastures and Climate Extreme Experiment

Funded by Meat and Livestock Australia Ltd (MLA, https://www.mla.com.au/) with co-investment from Western Sydney University, the Pastures and Climate Extremes (PACE) project was designed to provide novel insights into the potential impacts of future, more extreme, climatic conditions on pasture systems across Australia. The experiment ran between 2017 and 2020 and used technology inside a glasshouse to simulate different climatic conditions. The setup included 12 pasture species and mixed species sward types, with 10 different species commonly used in pasture-based meat and dairy farming including a range of C_3 and C_4 grasses. Legumes and native grasses (*Rytidosperma caespitosum*, *Themeda triandra*) were also included in the study. The experimental climate conditions examined in

this work focused on a winter/spring drought scenario involving a 60% reduction in precipitation based on a 128-year record of 650–750 mm annual precipitation events. The drought treatment operated in addition to a delayed autumn break that shifted the pattern of water availability at the end of the warm growing season (Pook et al., 2006; Kiem & Verdon-Kidd, 2010). Additionally, a subset of pasture swards was exposed to a +3°C warming treatment using infrared ceramic heaters in a factorial cross with the drought conditions. Pasture plots were 2.5 m × 2.5 m, with a core sampling area of 1 m^2 to determine annual and seasonal productivity above and below ground. Biomass harvests were sorted to account for proportional contributions of any weeds, and regular assessments of plant tissue chemistry were conducted for all species. Each plot was additionally monitored with a camera to track shifts in pasture canopy colour and cover, using daily imaging to examine short-term responses to changing environmental conditions. The outcomes of this project were used to inform strategies for maintaining sustainable pastures in Australia under climate change scenarios. The PACE facility is located at the Western Sydney University's Hawkesbury Campus at Richmond (NSW, Australia), and initial data products were made available to the public in 2019 (A. C. Churchill, formerly at the Western Sydney University, now University of Minnesota, pers. comm., 2020).

NPP Grassland: Charleville

The NPP Grasslands Charleville dataset comprises measurements of above- and below-ground biomass, productivity and litterfall data for a native C_3 and C_4 grassland near Charleville (26°24′07″S, 146°14′43″E, elevation 301 m above sea level) in southern Queensland. The NPP studies were conducted over a 12-month period from 1973 to 1974 using harvest techniques, and the data were used to calibrate a primary productivity model for livestock carrying capacity. Annual net primary production was estimated as the sum of above-ground peak standing crop (live + dead) and root increment. This dataset has been uploaded to a public repository (Table 1).

Miles and Condamine, Southern Queensland: Vegetation Assessment

An assessment of native grassland systems was undertaken at two sites (Sites 1 and 2) in the Miles and Condamine region of southern Queensland (Abbott et al., 2017). Field work was undertaken to sample natural vegetation based on the method developed by Tothill et al. (1992). Further walk-through samples were conducted for each of the sites to determine overall biodiversity. Biomass estimates were calibrated using 10 cut, dried and weighed quadrats for each site. Cover estimates were calibrated using 10 photographs of quadrats per site, which were classified into cover and bare earth using remote sensing (Abbott et al., 2017). Site 1 was dominated by native perennial grasses (*Aristida* sp.) and exotic perennial grasses (*Cenchrus ciliaris* or buffel grass), with approximately 10% native perennial grasses. Site 2 was dominated by the native perennial grasses *Eriachne mucronata* (≈43%) and *Chloris divaricata* (≈8%), along with a significant component of exotic perennial grasses: *Bothriochloa pertusa* (≈11%), *Megathyrsus maximus* (≈11%) and *Urochloa mosambicensis* (≈9%). Readers are referred to Abbott et al. (2017) for a full description of this work and access to the electronic database.

Unpublished or Unavailable Datasets

We know of a large amount of field observations collected in rangeland systems that have not been made publicly available, often because they pre-date the internet age. The amounts of digital and non-digital data that are stored in public and private computer servers or filing cabinets are understood to be large. Current capabilities and resources available to researchers are not sufficient to curate and publish those datasets, but this may be possible with adequate investment. For example, T'Mannetje & Jones (2010) summarise 73 grazing trials from northern Australia that collected biomass information and that were routinely sampled several times per year over multiple years. During a four-year period, Graetz (1980) collected samples of sites grazed by cattle or sheep in New South Wales. Holm et al. (2003) recorded shrub biomass and herbs, forbs, ephemerals and biennials, amongst others, over 11 years, four times per year, in 10 paddocks and four exclosures from 137 sites. These comprehensive datasets are not publicly available. Datasets may be tidied and error-checked, but before becoming operational, they need metadata and instructions on the codes used and the methods by which the data were collected.

Table 1. A compilation of publicly available rangeland productivity observations in Australia. Units are expressed as they appear in the original data source.

Name of NPP-biomass dataset	Spatial coverage	Spatial resolution	Temporal coverage	Temporal resolution	Link to data or reference	Applications	Limitations
GPPDI	Global	Measurements based on sampling of small field plots (from m^2 to 1 ha). Gridded data are half-degree latitude-longitude grid cells.	The point and gridded measurements included here cover the period from 1931 to 1996. This coverage does not include all years for all sites.	Annual NPP estimate in g C/m^2/year (carbon content of dry matter weight).	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1033	• Modelling • Natural resource inventory and management • Carbon accounting	• Temporal resolution for current modelling applications
NPP Multi-Biome	Global	The boreal forest study plots were between 0.09 and 0.25 ha in size. The tropical forest study plots were between 0.0025 and 4.4 ha in size. The C_3 and C_4 grassland study plots were between 0.0025 and 0.7 ha, and between 0.06 and 0.25 ha in size, respectively.	1939–1996	Generally, one month for grasslands and up to one year for forests.	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=653	• Modelling • Natural resource inventory and management • Carbon accounting	• Temporal resolution for current modelling applications
Nutrient Network: A Global Research Cooperative	Global	The core experiment will be a completely randomised block (environmental gradient) design with three blocks, 10 treatments per block, and three replicates per treatment ($n = 30$ total experimental units). Each experimental unit will be 5 × 5 m in size, with the experimental units separated by at minimum 1 m walkways. The corners of the plots should be marked permanently.	2007 – ongoing	Data collected during growing season. Biomass g/m^2 and cover (fraction).	https://nutnet.org/	• Modelling • Natural resource inventory and management • Carbon accounting • Rehabilitation of degraded landscapes • Land-use assessment/ Land-use changes	• Accessibility
NPP Multi-Biome: VAST Calibration Data	Australia	The observations were obtained by different authors from studies at 588 locations.	1965–1998	Annual NPP estimate in Mg C/ha/year. Above-ground phytomass in Mg C/ha. Above-ground fine debris litter mass in Mg C/ha.	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=576	• Modelling • Natural resource inventory and management • Carbon accounting	• Temporal resolution for current modelling applications

Name of NPP-biomass dataset	Spatial coverage	Spatial resolution	Temporal coverage	Temporal resolution	Link to data or reference	Applications	Limitations
AEKOS *Poaceae* Extraction, 2014	Australia	The data include vegetation records for the Poaceae family from the following dataset: ABARES Ground Cover Reference Sites Database, Biological Survey of South Australia – Vegetation Survey, Biological Database of South Australia, Corveg (Queensland), TERN AusPlots Rangeland Survey Program, Biological Survey of the Ravensthorpe Range (Western Australia).	1975–2013	Abundance, biomass and cover.	https://portal.tern.org.au/aekos-poaceae-extraction-2014/17370	• Modelling • Natural resource inventory and management • Carbon accounting • Rehabilitation of degraded landscapes • Surface cover • Land-use assessment/ land-use changes	• Temporal resolution for current modelling applications • Scale
Fuel biomass	Australia	Site estimations based on three transects of about 100 metres.	2001–2012	Measurements of above-ground grass and herb standing biomass and other structural characteristics. Biomass in Mg/ha.	https://figshare.com/articles/A_continental-scale_assessment_of_fuel_loads_and_consumption_by_wildfire/6203993	• Modelling • Natural resource inventory and management • Carbon accounting	• Temporal resolution for current modelling applications • Scale
The Australian Carbon Database v1.0	Australia	Dataset based on a literature search. A total of 621 observations from 157 sites were collated, describing 15 specific carbon pools (such as above-ground tree mass, grass leaf mass, soil carbon mass). Only 16 observations have accompanying error estimates, and only 15 sites have repeat measures of any kind. Median footprint of observations 0.5 ha.	1951–2012	Measurements of above-ground standing biomass and other structural characteristics. Biomass in kg/m^2.	Lawson et al. (2015)	• Modelling • Natural resource inventory and management	• Scale • Temporal resolution for current modelling applications • Accessibility
Pastures in Climate Extremes (PACE)	South East Australia, Plot experiment	Plots of $2.5\,m^2$	2017 – ongoing	Measurements of above-ground biomass (kg/ha) (refer to webpage for more information).	https://www.westernsydney.edu.au/hie/projects/PACE_pasture_climate_extremes	• Modelling	• Scale • Temporal resolution for current modelling applications

Name of NPP-biomass dataset	Spatial coverage	Spatial resolution	Temporal coverage	Temporal resolution	Link to data or reference	Applications	Limitations
NPP Grassland: Charleville	Charleville site, Queensland, Australia	Each study area covered 0.7 ha. Quadrats were 1 m^2.	1973–1974	Measurements of above- and below-ground standing crop were made every 2 weeks during the growing seasons; otherwise every 4 weeks over a 12-month period. NPP in g/m^2/year; Biomass g/m^2.	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=468	• Natural resource inventory and management • Surface cover	• Scale • Temporal resolution for current modelling applications • Accessibility
Miles and Condamine, southern Queensland: vegetation assessment	Southern Queensland, Australia	Each site consisted of five 1 m^2 quadrants, randomly distributed.	November 2016	Each site measured species composition, biomass kg/ha, total cover, litter cover and grass basal area.	Abbott et al. (2017)	• Natural resource inventory and management • Surface cover	• Scale • Temporal resolution for current modelling applications • Accessibility

In an attempt to understand past and current activities, and identify contributors and interest to form an Australian productivity field-site network and community of practice, we released a consultation to find data (irrespective of public or not) to inform the need for coordination. Unfortunately, despite widespread circulation, only eight people responded to the consultation request, and while this activity partly informed our thinking, the results are not presented in any detail here, but they are available and can be requested from the lead author.

The Proposed Way Forward

Scattered and privately held data, whether in analogue or digital form, need curation and consolidation. We have provided some examples of data that are publicly available in Australia, and we would like to use this contribution to initiate a conversation on this topic and excite future work in this space. For example, the TERN Data Discovery Portal displays 170 or 186 results when using "rangeland biomass" or "pasture biomass" as key searching words, respectively. These datasets are independent from each other. The commonalities between them have to be assessed by the user before deciding to incorporate them into their modelling system. The time required to assess and validate a dataset generated by another research group is often beyond the scope and budget of most projects. There are also concerns about formatting the data so that they can be shared publicly without breaking contractual obligations. In the following sections, we discuss how the existing data may be merged into a national rangeland productivity database. We propose a protocol for the creation of a National Net Primary Productivity and Biomass Database based on the existing recommendation for data collection in Australia, taking into consideration:

- the needs of different users;
- the need for a robust community of practice; and
- the need for an operational model to make the investment attractive to potential collaborators.

Australian Rangeland Productivity Database

Globally and nationally, researchers require well-tested validation approaches that are transparent and flexible (e.g. geographic scope, spatial resolution, protocol). There is a need for good practices and protocols to guide productivity model calibration and validation. TERN has developed a protocol (Held et al., 2015) for above-ground biomass collection. This protocol and the data-sharing practices from the AusPlots Rangeland Consultation Protocols Manual (White et al.,

2012) are used to inform research, management and conservation strategies. However, existing well-regarded protocols must be considered. McKeon et al. (2009) references the GUNSYND (McKeon et al., 1990) and SWIFTSYND (Day & Philp, 1997) protocols for collection of grassland data. These were developed to feed into the GRASP model (i.e. protocols were designed by modellers) and Aussie GRASS, and were well embraced by all rangeland states (Carter et al., 2000a,b; Richards et al., 2001). These protocols have been accepted by users and used to collect significant amounts of data. At the farm level, producers also use measurements of pasture biomass to assist in their management decisions, e.g. by visual estimation in rangelands and using plate meters to estimate pasture biomass in temperate grasslands (Catchpole & Wheeler, 1992). In fodder availability estimations, pasture biomass measurements are usually combined with information on pasture quality such as protein content, digestibility and soluble carbohydrate content. There appear to be insufficient channels to share these data, and if shared, the data would have to be built with industry and producer engagement and with appropriate checks to respect privacy and commercial confidence. Researchers and modellers do not share data unless a project that plans to collect field observations is under a contractual obligation to make the data publicly available. The 'best' database will vary based on users' needs. TERN follows the FAIR (Findable, Accessible, Interoperable and Reusable) Data Principles (Wilkinson et al., 2016). These principles are useful because they:

- support knowledge discovery and innovation;
- support data and knowledge integration;
- promote sharing and reuse of data;
- are discipline independent and allow for differences in disciplines; and
- move beyond high-level guidance, containing detailed advice on activities that can make data more 'FAIR'.

One approach is to classify the existing and new data into categories following the structure proposed by the GPPDI (Olson et al., 2011), where information is classified from Class A to Class C, representing reliability of the datasets. Here, the users will determine what level of information satisfies their needs and use the data accordingly. For example, in terms of understanding rangeland biomass and productivity for fire applications, and therefore for fire-related carbon emissions, the temporal dynamics of biomass and productivity are vital information. Fire risk in semiarid and arid rangeland and grassland is driven by biomass availability that is linked to rainfall in previous periods. So, data and models that support understanding of rangeland response to precipitation over time are crucial inputs in fire modelling systems. Therefore, data collection should span a significant temporal period to capture biomass variation over time in response to precipitation, both within and between years. This will also help validate remote sensing biomass observations that can be used in fire fuel availability analyses. In this example, long-term information is a vital characteristic to achieve a satisfactory model performance, and the same could be argued for fodder productivity models. For this type of user, long-term observations could rank higher than detailed characterisations of the species composition and structure at a specific site. A well-detailed dataset about species composition and structure may be the most important characteristic in ecological and grazing impact studies. Therefore, a database should be compiled in a way that is flexible enough to discover information and characteristics about the entries based on the different users' needs.

Data Sharing Practices

One of the biggest challenges in this proposal is to create a robust community of practice willing to follow the proposed protocols and contribute their data to a national database. The community of practice will need to recognise the intellectual property of data and the need to develop license arrangements for data usage, whether for research, education and extension or other purposes. Use of data for commercial applications will need to be considered. The intellectual property, both in the original and curated data, will need to be transparent for potential users. Setting up the data as a tangible commercial asset will provide flexibility and assist collaborative arrangements, and will help establish a framework for continuous developments into the future. License arrangements may be free or attract fees and royalties depending on the data application. We understand the community of practice as a social learning system (Wenger, 1999). Meaningful

learning requires participation of people with a common goal. The participants should have a collective understanding of 'what matters' and how to engage to generate more knowledge. Some of the main attributes for a functional community of practice are: imagination, engagement and alignment. We recommend a dynamic model where stakeholders, funders and end-users can benefit from being part of the community of practice and having access to the updated and curated database.

The Global Carbon Project (GCP, https://www.globalcarbonproject.org/) follows a similar protocol, and some of the benefits are:

- Contributors have early access to the database so they can prepare publications before it becomes publicly available.
- Stakeholders and funders can show the value of data collection through the products and services that are provided based on the data, which without the existence of the database would not be possible to achieve.
- To become part of a large group of users and beneficiaries that can provide feedback about how to improve data collection and how to improve end-products.

Here, the outcome is to offer public access to a biomass database. Based on the GCP protocol, we propose that contributors to these datasets should have access to the data beforehand. This means that information can be accessed well in advance of the data being released to the public, giving researchers the opportunity to prepare and lead publications. In this scenario, the database is curated by the contributors before being publicly released. We also propose to launch the database with a paper, with all major data contributors as co-authors, for a data journal. The associated database will have a Digital Object Identifier (DOI), which can be used to track the impact of the database and count citations for the contributors of the database.

Contributing organisations may apply for funding to organise workshops with other contributors, leading to the production of scientific material using the updated data, expanding networks and developing new collaborations. New publications should target highly ranked journals. Being part of the community of practice will give researchers the opportunity to collaborate in future publications, expand their networks, promote their work and explore new research opportunities. The proposed approach should encourage an increased number of people to collaborate so that the database can attract more entries.

Formatting existing data for public sharing can prove cumbersome due to time and budget constraints. Data collected by private companies (e.g. Cibolabs in Australia, https://www.cibolabs.com.au/) or public institutions cannot be shared publicly in the current format due to contractual obligations or formatting issues. The time and labour capacity required to format the data can be expensive. Public institutions, including universities and research government organisations, may not provide the required support to researchers for long-term data management (Tenopir et al., 2011). Therefore, we suggest giving small companies and institutions or independent researchers the opportunity to apply for grants to format their data and make it publicly available through a rangeland database. If funding investments could be arranged, TERN may be an excellent choice as a partner organisation in leading and managing the database. Public access to the data may be best provided by developing collaborative arrangements with agencies that have specialised systems for public and collaborative access to large datasets, such as Geoscience Australia and the Bureau of Meteorology. An alternative to the above may be to consider a larger, nationally coordinated project to develop the rangeland database, which has been done in the past for other datasets. Examples are the development of the Bureau of Meteorology weather data through the CLIMARC (Computerising the Australian Climate Archives) and SILO projects with funding from Land & Water Australia; runoff and streamflow data throughout Australia via a LWRRDC (Land and Water Resources Research and Development Corporation) funded project (Clarkson et al., 2000); and soils data through a number of agencies. Some of the advantages of data management and sharing are (Tenopir et al., 2011):

- Different interpretations or approaches to existing data contribute to scientific progress.
- Well-managed, long-term preservation helps retain data integrity.
- When data are available, (re-)collection of data is minimised; thus, use of resources is optimised.

- Data availability provides safeguards against misconduct related to data fabrication and falsification.

To which we add:

- In situations where the researcher identifies the need to collect new data, we recommend following existing protocols in order that field observations can be easily incorporated into the national database and data sharing is possible.
- Publish the data in an open and discoverable repository: the data do not necessarily have to be open to the public, but the public should be able to know that the dataset exists.

Conclusions

There is a collective perception in the Australian scientific and modeller community that there is a lack of field observations of rangelands. We found several examples of datasets that, if combined, would cover a significant proportion of Australia's rangeland systems. Data exist but are scattered and need consolidation for ready access. We also contend that there is a vast amount of digital and non-digital data stored in public and private computer servers or filing cabinets. Retirement of current senior scientists from universities, government agencies and allied organisations in the near future could result in a significant amount of data collected over the years becoming unavailable if not properly archived in electronic databases.

We propose the development of an Australian Rangeland Productivity Database. If this concept is accepted, with either industry funding or as a government-funded project, then the next challenges revolve around ways to implement it, including selection of an organisation to lead such a project. The establishment of a national database will help to improve estimates of rangeland systems (productivity, structure) and modelling platforms, and to prioritise unrepresented ecoregions in future field studies. We identify potential affiliates of this community and users of the proposed rangeland productivity field-site network.

Compiling existing datasets is a major task that the TERN (Terrestrial Ecosystems Research Network) could potentially achieve over future years. This task must consider that the user should be able to assess observations through a portal that can be easily queried to filter for desirable information. Researchers find it difficult to transfer information to the existing platforms, and the value of making data discoverable has not been quantified. TERN should consider the consolidation of a national rangeland productivity database, based on existing data, as one output. We emphasise that there is limited time to undertake this work. Such datasets should be regarded as a national asset that otherwise could be lost. The rangeland productivity community is seeking ways to streamline data collation and use. Incorporating biomass measurements in the TERN SuperSites protocol could be a plausible solution in the short term. The rangeland productivity community is seeking long-term monitoring and a sustainable funding model. TERN would need to manage the governance and the industry advisory committee.

Australian scientists have the tools needed to succeed in creating a robust community of practice. Government, public and private institutions should be able to provide the required resources to build this community and establish long-term collaboration across disciplines. This community should promote 'good' data sharing practices and identify project opportunities and channels to collaborate in such projects. Improved science flowing from development of the database would deliver benefits to the rangelands through better management of high-priority issues, such as tracking and managing land condition, ecological restoration and protection, drought, fire and climate change, and reduced sediment flows to waterways and the Great Barrier Reef.

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Waterhole in the Mitchell River catchment, Cape York, Queensland (Photo: Nathan Dyer).

North West Queensland Rangelands, Upper Burdekin, Indian Couch Invasion (Photo: Brett Abbott, 2006).

COVID-19 Pandemic: Tackling 'Infodemics' Through an Integrated One Health–Social Science Approach

Noore Alam[1], and Cordia Chu[1]

Abstract

The novel coronavirus disease 2019 (COVID-19), which was first identified in Wuhan city, China, in late December 2019, has now spread globally with over 43 million people infected and about 1.16 million deaths as of 30 October 2020. COVID-19 is a novel and highly transmissible disease where little is known, which is why health authorities and the public alike have reasons to be concerned. With the spread of the disease, there has been an 'infodemic', which is defined as an influx of all kinds of information, including authentic information and also rumours, misinformation and conspiracy theories about the origin, prevention and treatment of the disease. With the growth of infodemics over social media and mass media, prejudicial and xenophobic acts became more evident, presenting additional challenges for health authorities. Effective control of pandemics such as COVID-19 thus requires large-scale, multifaceted response measures including risk communications. A transdisciplinary collaborative One Health approach has been increasingly advocated as an effective strategy to address diseases that occur at the human-animal-ecosystem interface. Similarly, the role of social science in risk communications in recent epidemics such as Ebola has been widely acknowledged. Timely interdisciplinary reviews, including a social and behavioural sciences lens, are needed to optimise the pandemic response through effectively combating communication challenges associated with infodemics and many other challenges in future epidemic responses.

Keywords: infodemic, coronavirus, pandemic, misinformation, One Health, whole-of-government pandemic plan, social science, risk communications

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Introduction

Several cases of severe acute respiratory syndrome (SARS) were first reported in Wuhan City, Hubei Province, China, in late December 2019. The causative agent was soon identified as a novel coronavirus. It was called severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) and is a new strain of coronavirus not previously identified in humans. Coronaviruses are a group of viruses that can cause illnesses ranging from a common cold to more severe diseases such as SARS and Middle East respiratory syndrome (MERS) (World Health Organization, 2020a). The SARS-CoV-2 virus that causes the novel coronavirus disease 2019 (COVID-19) spreads from person to person primarily through respiratory droplets from an infected person. Epidemiological evidence collected from the initial patients in Wuhan indicated links to a large seafood and wild animal market, suggesting that the virus may have emerged from an animal source (Zhu et al., 2020). Within days of first identification in Wuhan, the COVID-19 outbreak spread to other parts of China and several other countries. Outbreaks and clusters of the disease have since been observed in over 200 countries and territories, with over 43 million cases and 1.16 million deaths as of 30 October 2020 (Figure 1) (World Health Organization, 2020c).

The World Health Organization (WHO) declared COVID-19 a pandemic on 11 March 2020. In Queensland, the first case of COVID-19 was reported in late January 2020. The total number of confirmed cases has since risen to 1171, with six deaths in Queensland as of 30 October 2020 (Figure 2) (Queensland Health, 2020).

As fears of COVID-19 grew, so did information about the virus – some of it authentic and reliable – but also the false, the fabricated and the folk theory information that was deliberately deceptive (BBC News, 2020; Thomas, 2020). During the early days of the epidemic, the disease was variously called the "Chinese coronavirus" or the "Wuhan coronavirus", which was prejudicial and discriminatory towards Chinese people (Shu, 2020). On 11 February 2020, WHO gave a formal name to the disease – coronavirus disease 2019 or COVID-19 – without referring to a place or the ethnicity of its origin (World Health Organization, 2020e).

Figure 1. Number of global COVID-19 cases, and cumulative number of cases and deaths.

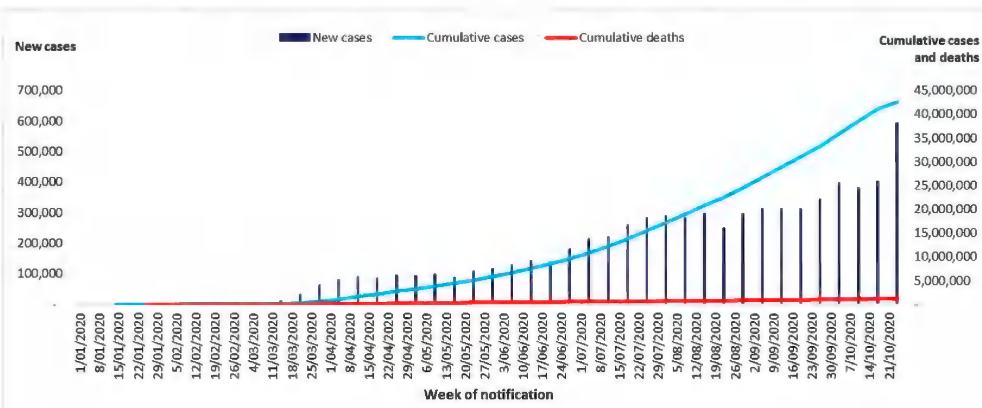
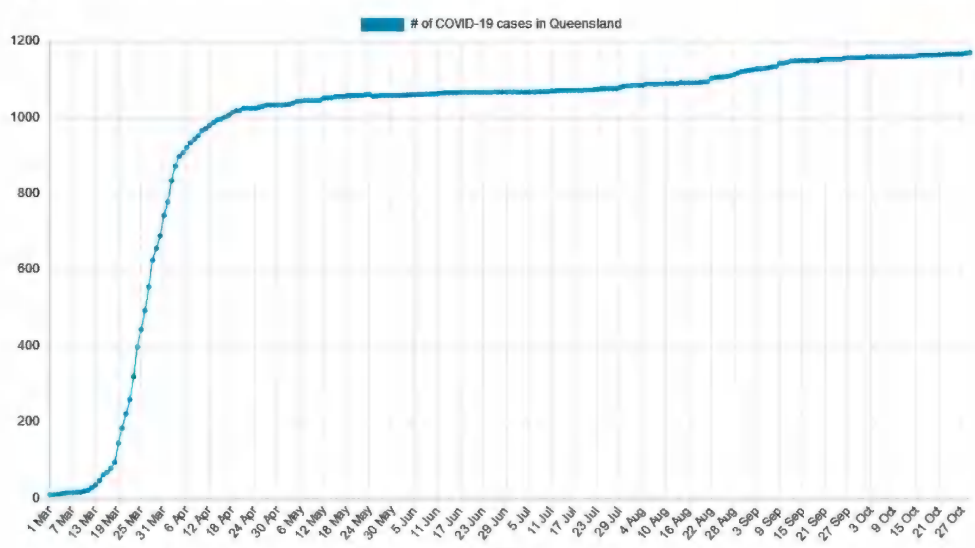


Figure 2. Cumulative incident cases of COVID-19, Queensland, Australia.



The ethnic stereotyping linking the origin of the virus, along with limited knowledge and uncertainties about the disease, fuelled rumours and misinformation, escalating fear, panic buying, social unrest and substantially impacting global financial markets (BBC News, 2020; United Nations Development Programme, 2020). Health authorities in many countries thus faced challenges on two fronts: controlling the spread of the disease; and addressing the growing rumours, misinformation and associated social and economic impacts. The scale and magnitude of misinformation spread worldwide have prompted WHO to set up a new information platform called WHO Information Network for Epidemics (EPI-WIN) to counter the misinformation surrounding COVID-19 (World Health Organization, 2020d). As WHO Director-General Dr Tedros Adhanom Ghebreyesus said, "We're not just fighting an epidemic; we're fighting an infodemic" (Zarocostas, 2020). The term 'infodemic' is defined as the rapid spread of information of all kinds, including rumours, gossip and unreliable information (World Health Organization, 2018). In this article, infodemic refers to rumours and misinformation about the origin and spread of COVID-19.

Infodemics in General Health Emergencies

During an epidemic, people tend to develop their own hypotheses about the origin and mode of transmission of the disease (Stadler, 2003). Often misinformation spreads more rapidly than the disease itself – thanks to the prolific use of smartphones, the internet and social media. Other than sharing unverified facts, internet-based infodemics may also include genuine misunderstanding of facts, and equally they may be a result of deliberate deception (Zhang et al., 2015). Speculation foments from not only lack of information but also unclear or conflicting information from multiple sources. Unlike formal media such as television, radio and official internet websites, messages spread through informal media, such as internet blogs and social media, are prone to misinformation as it is difficult to verify the authenticity of the information received (Sunstein, 2014). In times of health emergencies, while most false rumours stem from an absence of reliable data, or unclear information from a trustworthy source, they may also be due to inappropriately or infrequently communicated public health messages (Sunstein, 2014). There are instances where rumours may also generate from a state of panic, especially when it is caused by a novel pathogen. For example, HIV/AIDS was long speculated to be a foreign disease in some regions in the absence of a strong and effective public health communication (Stadler, 2003). Similarly, there was a notion that Ebola was a laboratory-generated virus (Loukatou et al., 2014). During the influenza (H5N1) epidemic in 2004, WHO identified 40 different rumours in circulation, only nine of which were verified to be factually correct (Samaan et al., 2005). Rumours pose significant challenges to the effective communication of evidence-based information, which is crucial for the adoption of recommended health actions by the public (Luth et al., 2013).

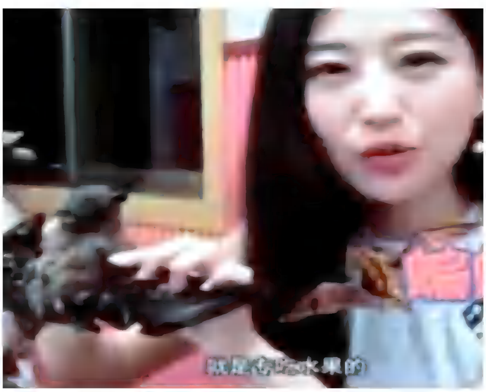
Infodemics Surrounding COVID-19

As COVID-19 crossed international borders, panic started to grow amid an influx of information from numerous sources including government health authorities, international organisations such as the WHO, and public media such as radio and TV. Messages were also outpouring through various internet websites, blog posts and social media regarding the source of the virus and the methods of its transmission. Alongside authentic information from competent authorities worldwide, various false claims and conspiracy theories also emerged and spread through social media (Thomas, 2020). Following the emergence of SARS-CoV-2, and at a time when no specific animal species had been identified as a definitive point-source of the virus, a YouTube™ video showing a Chinese woman eating bat soup emerged and was widely circulated through the internet media, suggesting bats were the source of the outbreak (Figure 3) (YouTube, 2020). The video, which was originally filmed in 2016, prompted outrage among some users of online social media, with some people believing that Chinese eating habits had caused the outbreak (BBC News, 2020). The video was unavailable at the time of submission of this paper.

Although past evidence suggests that animals such as civets, camels, bats or pangolins are the reservoirs of coronaviruses, the exact source of COVID-19 is yet to be determined. Yet

rumours, misinformation and conspiracy theories were spreading rapidly while officials around the world were fighting to contain the disease (BBC News, 2020). Lately, there have been claims that COVID-19 was manufactured at a Chinese laboratory (Andersen et al., 2020), or it was linked to the rollout of 5G telecommunications networks in Australia (Wood, 2020). These claims have no scientific basis and were dismissed by scientists and competent authorities worldwide (Andersen et al., 2020; Australian Radiation Protection and Nuclear Safety Agency, 2020).

Figure 3. An internet video clip showing a Chinese woman holding up a cooked bat.



The Impact of Infodemics on COVID-19

The ramifications of the COVID-19 pandemic on individuals, society and the global economy are enormous, and are partly exacerbated by infodemics which have led to irrational public behaviour such as panic buying and stockpiling of food products, toilet paper and hand sanitiser. In a small number of extreme cases, physical fights fuelled by extreme anxiety have occurred in retail stores over toilet paper and other domestic essentials (Lucy, 2020). False rumours have also resulted in xenophobic behaviour and racial vilification of Chinese nationals in foreign countries (Rendall, 2020). Businesses run by individuals of Chinese origin were particularly hit by a spate of racially motivated abusive behaviours and attacks, and calls for avoidance of their businesses (Rendall, 2020). Although there was no evidence that Chinese nationals were at higher risk of having the disease than other people, deceptive messages have the potential to damage the social fabric and community harmony at a time when societal unity and coherence are needed more than ever.

Deliberately deceptive or fabricated information can also damage the credibility of important public health messages communicated by health authorities during an epidemic. For example, in late January 2020, a fake Media Release, said to be issued by the Queensland Government Department of Health, emerged and spread through social media, allegedly advising people to limit non-essential travel to Wuhan, China, as well as several local areas in Australia with high ethnic Chinese populations (Figure 4) (Rendall, 2020). The use of the official logo of the Department and its web address made the statement appear credible, although a simple verification of this statement with the Department's official website showed this to be fake news. Misinformation or lack of reliable information may have caused many patients with other health conditions to avoid accessing healthcare services for fear of contracting COVID-19 (Mackee, 2020). There were reports of drastic falls in attendance at hospital emergency departments in Australia, the UK, Europe and Canada (Jennings, 2020).

Figure 4. Fake, racist statement on social media targeting Chinese residents.

Department of Health media release | Queensland Health
A list of current Department of Healt
www.health.qld.gov.au

https://www.health.qld.gov.au/news-events/doh-media-releases

QLD Department of health media release QLD issues level 3 health warning for coronavirus, advises against nonessential travel to Wuhan, China, Sunnybank, Sunnybank Hill, Runcorn, Eight Mile Plains and all populated areas with Chinese nationals of ratio of 1 to 3 non-Chinese Australians.

Since the disease was first detected, unprecedented control efforts have been undertaken by health authorities worldwide. Whilst there is

significant evidence of global sharing of knowledge about the disease, as well as massive scientific effort and innovation such as development of an effective vaccine against the SARS-CoV-2 virus (The Lancet, 2020), there are also reports of shortcomings in many aspects of response measures including dealing with infodemics (Weismueller et al., 2020). Furthermore, there are widespread criticisms of political leadership in many countries for over-politicising (Chappell, 2020; Weismueller et al., 2020) or underestimating the threat of the pandemic due to poor health literacy, which itself is an underestimated public health problem (Paakkari et al., 2020). Adding to these challenges is the fact that current advances in communication technologies can present risks as well as benefits. Reliable health and behavioural messages can spread rapidly, but so too can misinformation and fake news.

It is therefore extremely important that health experts and political leaders work together on sharing evidence-based information and devising appropriate risk communication strategies to deliver accurate and reliable information to counter infodemics, which have the potential to undermine response initiatives (Stadler, 2003). Public health authorities, both nationally and globally, should therefore consider inclusive and well-structured response measures incorporating diverse disciplines and sectors beyond their respective professional and cultural silos. To this end, a One Health (OH) approach has emerged as a holistic framing to bring together disciplines such as public health, veterinary medicine, environmental and ecological health to tackle health problems that stem from environment-human-animal interactions and epidemics.

An Integrated One Health–Social Science Approach

There has been an increased realisation that the health of humans is intrinsically linked to the health of animals and the ecosystems in which they reside (van Helden et al., 2013). The origin, transmission and impacts of infectious diseases are influenced or strongly shaped by many factors, such as environmental, physiological, social and cultural conditions. Effective control of infectious disease epidemics such as COVID-19 therefore require a broad-based, holistic One Health (OH) approach, which recognises the interconnectedness between the health of people and the health of animals and our shared environment (One Health Commission, 2020). The OH paradigm emphasises cooperation and interdisciplinary collaboration to promote health and wellbeing among people, animals and the environment (Woodward et al., 2018). The OH approach thus emphasises collaboration between multiple disciplines and institutions – working locally, regionally, nationally and globally – for the benefit of the health and wellbeing of people, animals and the environment (One Health Commission, 2019). Although the fundamental concept of OH is not new, its formal recognition and systematic use have been evident only in recent years in diverse areas, such as combating antimicrobial resistance (Robinson et al., 2016), zoonoses (Woodward et al., 2018) and ensuring food safety (Institute of Medicine, 2012). The traditional OH approach to disease prevention and control typically integrates those broad sectors and disciplines that are directly linked with disease ecology and the transmission and treatment of diseases. However, to date there has been limited use of other non-health disciplines, such as social science and communications, within an OH framework to deal with psycho-social aspects surrounding an epidemic or pandemic (Khan et al., 2018), although the role of social science in risk communications, not necessarily as part of an OH approach, was widely advocated during the West African Ebola epidemics (Dhillon et al., 2015; Sumo et al., 2019).

There has been growing attention to the social dimension of infectious disease emergence and transmission (Wolf, 2015). The need for social science interventions and contributions in epidemic, pandemic and other health emergency response measures is thus widely acknowledged and applied (Craddock et al., 2015; Shah, 2020; Woldehanna et al., 2015; World Health Organization, 2017b). Alongside scientific measures such as laboratory testing of pathogens, immune response, and vaccine research and development, public health measures focusing on prevention and protection should adopt an enhanced One Health–social science integrated approach (the 'integrated approach') to strengthen the control measures against pandemics. The traditional OH approach advocates for collaboration between public health, veterinary health and environmental or ecological health because of their interconnectedness in the

emergence and progression of diseases that occur in the human-animal-environment interface. However, due to many uncertainties and the complexity of dealing with pandemics caused by novel pathogens such as SARS-CoV-2, the scope of the traditional OH approach needs to be broadened by incorporating other related disciplines and sectors. To this end, we propose an integrated OH approach where social and behavioural sciences and other related disciplines can be incorporated into the traditional OH model. Within the framework of the proposed integrated approach, the inclusion of health educators, communication specialists, social scientists, psychologists and social media experts is essential alongside physicians, veterinarians, public health officials and laboratory scientists to foster much greater cooperation and inclusiveness, and thereby improve risk communication outcomes within the community.

Incorporating Risk Communication into the Integrated Approach to Deal with Infodemics

Risk communication is both an art and a social science, and is integral to epidemic responses (Vaezi et al., 2020). During an epidemic, the message to be communicated should be science based, culturally appropriate and easy to understand for all members of the affected communities, including those with low literacy (Good Calculators, 2020). Methods of communication should be innovative, interesting, and targeted to hard-to-reach people, e.g. remote or marginalised communities. Another equally important aspect of risk communication is an understanding of community risk perceptions and an appreciation of why a community perceives something in a particular way. However, risk communication is increasingly becoming a major challenge in combating emerging diseases in today's globalised world. It is essential that the authority initiating risk communication gains community trust and confidence about the health messages it delivers. Building trust and engaging with affected populations is one of the most important steps in effective risk communication (World Health Organization, 2017a). During the West African Ebola epidemic in 2008–2009, lack of community participation and failure to tackle misinformation were blamed for causing a combination of community mistrust, non-cooperation and lack of confidence in government responses to the epidemic (Hayden, 2019). Government response measures were characterised as a top-down and siloed approach with limited involvement of relevant disciplines and communities (Ntumba et al., 2019). Thus, the need for breaking down the traditional siloed approach has never been greater or more urgent. Effective and timely communication is crucial to the success of epidemic control measures, and risk communication is increasingly acknowledged as an essential element of response to health emergencies (Cipolla et al., 2015). The International Health Regulations (2005) identified risk communication as one of the 13 core capacities all countries must attain (World Health Organization, 2005). Effective risk communications and community engagement have proven to be integral to the success of responses to major public health events such as SARS, MERS, the influenza (H1N1) pandemic and Ebola (World Health Organization, 2020f). However, the risk communication and community engagement strategies applied to these and other epidemics varied markedly, and while there are no standard risk communication strategies that can be practically possible to implement across all epidemics and pandemics due to their unique nature and circumstances, identification of common areas where the proposed integrated approach can be applied could effectively harness the overall response initiative across a spectrum of control measures ranging from enhanced surveillance, including rumour surveillance (Samaan et al., 2005), to media management including social media monitoring (Fung et al., 2015) and risk communications (Sell, 2017). Table 1 illustrates the proposed structure of an integrated approach to risk communications to deal with infodemics. The proposed structure is built upon the WHO guidelines for risk communication (World Health Organization, 2017a).

During an epidemic, community distrust makes disease control measures extremely difficult, potentially resulting in the persistence of the disease (Dhillon et al., 2015). The OH integrated approach would focus on achieving community and civil society engagement to counter or dispel any negativity towards the response initiative. For example, during the West African Ebola epidemic in 2015, response teams reportedly faced an enormous challenge in gaining community trust as the affected

community tended to hide the sick and conduct funerals and related rituals in secret, against public health advice, making effective epidemic response extremely difficult (Dhillon et al., 2015). Thus, social barriers such as this, which could potentially hamper the control measures for COVID-19, need to be addressed through a combination of social science, including communication specialists, and epidemiological and medical expertise.

Against the backdrop of the emerging global human catastrophe of the COVID-19 pandemic, it is reasonable and indeed normal for the public to search for information about the origin of the virus that caused the disease. The provision of timely and accurate identification of the source and information on modes of disease transmission would help enormously in the prevention, containment and control of future pandemics.

Table 1. Risk communication measures to counter infodemics using the integrated approach with lead roles of communication specialists, social scientists and psychologists.

<table>
<tr><th>Action</th><th>Scope</th><th>Methods</th></tr>
<tr><td>Identify</td><td></td><td>Risk identification</td></tr>
<tr><td>Issue identification</td><td>Infodemics in circulation:
• Disease characteristics.
• Cause or source of disease.
• Modes of transmission.
• Symptoms.
• Seriousness (hospitalisation, recovery or death).
• Treatment options.
• Government response.</td><td>Monitoring of community perception and behaviour through formal and non-formal media including social media.</td></tr>
<tr><td>Source identification</td><td>Sources of the infodemics:
• Mass-communication media (TV, radio, newspapers, internet).
• Social media.
• Scientific journals.</td><td></td></tr>
<tr><td>Respond</td><td></td><td>Risk communication</td></tr>
<tr><td>Develop</td><td>Accurate, science-based, easy-to-understand messages for the public.</td><td>Targeted:
• Mythbusters.
• Frequently asked questions.
Non-targeted:
• Periodical updates of events including daily situation reports.
General topical information:
• Brochures, pamphlets, internet resources.</td></tr>
<tr><td>Disseminate</td><td>Public and private networks including government agencies, health authorities, scientific bodies, professional associations, clubs and communication organisations.</td><td>Media releases, public awareness campaigns in radio, TV, newspapers, internet websites and social media.</td></tr>
<tr><td>Evaluate</td><td></td><td>Surveillance and evaluation</td></tr>
<tr><td>Assess</td><td>Effectiveness of information management and risk communication.</td><td>Systematic surveillance through an authoritative platform to assess:
• trend of infodemics;
• how public health information is communicated and its effectiveness; and
• any changes to community perception.</td></tr>
</table>

Systematic surveillance and response to infodemics as part of a comprehensive communication strategy within an authoritative platform have proven benefits in the current COVID-19 pandemic. For example, the Queensland Government's whole-of-government pandemic plan, which is built upon the Australian Health Sector Emergency Response Plan for Novel Coronavirus (COVID-19) (Australian Government, 2020) and the WHO Pandemic Influenza Risk Management Guide (World Health Organization, 2017c), is a comprehensive approach to pandemic prevention, preparedness, response and recovery, with multi-dimensional strategies. Its communication strategy is built upon the principles of trust, empathy, consistency, integrity and collaboration (Queensland Government, 2020). An open, transparent and inclusive structure of communication under the Crisis Communication Network is a cornerstone of the Queensland Government's crisis response to ensure that the government maintains its brand credibility as a trusted, authoritative source of accurate, reliable and timely information so that Queenslanders feel safe, supported and informed during an outbreak (Queensland Government, 2020). Another example is the WHO's authoritative information and communication strategies which include a dedicated repository of information such as holding a catalogue of COVID-19-related misinformation and resources, including 'mythbuster' facts in videos and texts in easy-to-understand language (World Health Organization, 2020b,d).

A dedicated clinical and social science-based information and communication authority within the proposed integrated approach can be useful not just in rumour surveillance and risk communication. Its application can be as diverse as active case finding, contact tracing, compliance with social distancing and quarantine orders served by health authorities to prevent person-to-person transmission of the disease, media scans and media briefings, and community engagement in response initiatives. While many of these measures may have been undertaken already by different authorities at different levels, doing so within the framework of an organised, transdisciplinary collaborative plan such as the integrated approach would help prevent any unnecessary, costly responses to deal with the double challenges of the epidemic. Enhancing the effectiveness of the pandemic response and reducing the social and economic cost of the pandemic and the infodemic phenomenon can be achieved through strong coordination and collaboration among governments, coupled with clear and transparent communication strategies both locally and globally (United Nations Development Programme, 2020).

The integrated model, however, should not be treated as a 'one size fits all'. OH has faced numerous challenges in designing, and implementing transdisciplinary collaboration during real-life health emergencies (Ribeiro et al., 2019). For example, the engagement of diverse disciplines in an integrated model often leads to conflicts of focus and priority because of the diverse interests of those included. This could escalate information gaps and even coordination challenges, hampering the purpose of an effective and accelerated control initiative. In their qualitative study, Johnson et al. (2018) identified 'siloed' mentality, which they defined as "exclusive mentality that can inhibit cross-sectoral communication and collaboration", as the main barrier to OH implementation. The siloed mentality leads to conflicts of interest between participating sectors and disciplines, and lack of inter-sectoral trust and communications (Johnson et al., 2018) as was evident in past epidemics such as SARS and Ebola (Craddock et al., 2015; Woldehanna et al., 2015; Woodward et al., 2018). Moreover, the integrated model requires adequate provision of resources, both financial and human, to mobilise and engage for a protracted period of time, especially in a novel pandemic such as COVID-19. This may be a major impediment for low- and middle-income countries.

Conclusions

Despite acknowledged limitations, and based on the recent past and ongoing experience of Ebola (Dhillon et al., 2015) and COVID-19, respectively, a well-designed communication strategy within an integrated One Health–social science-based epidemic control regimen has great potential to enhance the effectiveness of responses to the multiple challenges of an epidemic, including dealing with those that are unique to zoonotic disease outbreaks (Ribeiro et al., 2019; Woodward et al., 2018) or those associated with novel pathogens such as the SARS-CoV-2 pathogen that causes COVID-19 (Brydges et al., 2020). Health authorities around the world need to evaluate past collaborative

approaches to other epidemics, or lack thereof, and employ a holistic view of the epidemic and accordingly devise appropriate, situation-specific communication strategies by incorporating relevant non-health disciplines into the traditional OH model. Local and nationally designed risk communication strategies with their respective integrated approaches should be harnessed with global communication and response initiatives within the framework of the International Health Regulations (World Health Organization, 2005). Leveraging experience from the current pandemic and to better prepare for the next pandemic, health authorities around the world might consider implementing the proposed OH integrated approach to deal with infodemics while COVID-19 is still prevalent, and well before the next epidemic or pandemic, so that a dedicated cross-disciplinary team is familiar with their roles and functions, and any communication gaps can be addressed appropriately.

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Author Profiles

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Professor Cordia Chu AM, Director, Centre for Environment and Population Health, Griffith University, has a background in medical anthropology and sociology with expertise in ecological public health, reproductive health, health promotion and integrated health planning. She is committed to ensuring that research is useful, usable and used through translational research and capacity building, particularly in linking the environment, health strategies and sustainable development. Her recent focus has been on building a research consortium for One Health, global health security, climate action and sustainability. Professor Chu has published five books, over 220 journal articles and chapters, two policy guidelines, four research communication booklets, 16 training manuals, five documentaries films, 24 international consultancy reports and one WHO regional guideline.

The Legacy of the International Biological Program in Australia

Alison Specht[1], and Raymond L. Specht[2]

Abstract

The International Biological Program (IBP: 1964–1974) was initiated by the International Council of Scientific Unions (now the International Science Council, ISC) to promote the world-wide study of production on land, in freshwaters and in the seas, the potentialities and uses of new and existing natural resources, and human adaptability to changing conditions. The IBP was the first of a series of global initiatives created to promote international collaboration around big environmental science questions since the Second World War. We present a brief review of similar initiatives that preceded and followed it, and then describe the operations and outcome of the IBP in Australia based largely on the personal experience of Raymond L. Specht (RLS), who was convenor of the Australian PCT section: productivity of terrestrial communities; production processes; and conservation of terrestrial communities. Despite the absence of any dedicated funding for the IBP in Australia, RLS was able to bring a team of interdisciplinary researchers to The University of Queensland and provide them with state-of-the art research facilities. This was the focus for many national and international exchanges, and several important outcomes. RLS, with the support of the Australian Academy of Science (AAS), enabled the first national survey of the conservation status of plant communities (a target of the IBP for each country) and developed it into an objective assessment long after the IBP itself had ended, laying the foundations for a comprehensive, adequate and representative national reserve system. Much more could have been produced if adequate funding had been provided for the program, reducing the reliance on the commitment and enthusiasm of individual researchers.

Keywords: International Biological Program (IBP), International Science Council (ISC), Australian Academy of Science (AAS), interdisciplinary research, conservation of terrestrial communities

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Introduction

Advances in science depend on sharing ideas. Various means have been employed over the centuries to enable this, from salons to synthesis centres, from exhibitions to conferences (Specht, 2017). Initiatives to support and facilitate global collaboration in the ecological and biological sciences may seem to many as very recent responses to issues like global climate change or biodiversity depletion. Such initiatives have existed, however, for more than one hundred years, with an uneven history not always well understood.

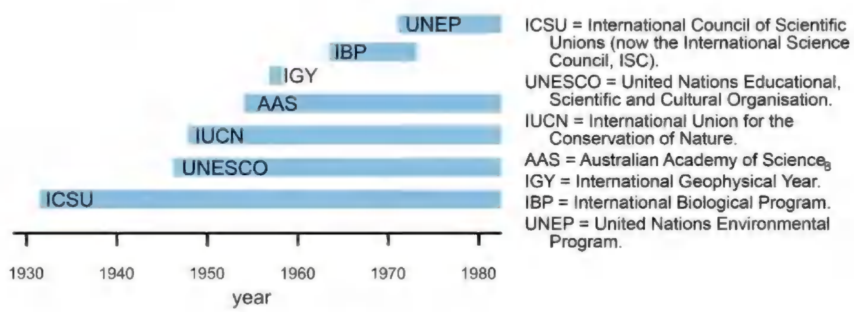
Arguably, the first step in the 'modern' phase of research collaboration started in 1899 with the establishment of the International Association of Academies (IAA), of which the Royal Society of London (established in 1660) was a key member. In 1919, the International Research Council (IRC) and the International Union of Biological Societies (IUBS) were established, the latter continuing until the present day. The Australian National Research Council (ANRC) was established in 1921, partly to represent Australia on the IRC (Fenner, 2008). Ten years later the International Council of Scientific

Unions (ICSU) was founded, one of the earliest of the scientific unions (Figure 1), and in 1947, after the interruption of the Second World War, the ICSU established a formal relationship with the newly formed United Nations Educational, Scientific and Cultural Organization (UNESCO), which was closely followed by the International Union for the Conservation of Nature (IUCN) in 1948. The concerns of the time were strongly influenced by effects of the traumas of the Second World War on human populations and resource availability, although conservation of natural resources for their own sake gained some traction. In 1954, the Australian Academy of Science (AAS) was created, and the AAS has subsequently managed, to a large extent, Australia's participation in international scientific initiatives.

In 1951, prior to the creation of the AAS, one of the biggest scientific activities initiated by UNESCO was the Arid Zone Programme, which evolved into the Arid Lands Major Project in 1956 and lasted until 1964 (Heymann, 2020). The focus on arid lands was timely, as concern about drought, desertification and famine in several countries coincided (see Ratcliffe & Huxley, 1947, for an Australian example). Among the outputs of the Arid Zone Programme significant to the present article was a Guide Book for scientists and engineers to produce "integrated surveys" of landscape using appropriate interdisciplinary research methodologies. The Guide Book was edited by Bertram Thomas Dickson of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and was published in 1957 (Dickson, 1957). The Arid Zone Programme paved the way for a new collaborative, interdisciplinary approach to common challenges, including the causes of climatic change (Heymann, 2020).

The International Geophysical Year (IGY), which spanned 1957–1958, was the main incentive for the creation of the subject of this article, the International Biological Program (IBP). The IGY was sponsored by the ICSU, *inter alia*, to undertake a comprehensive global study of geophysical phenomena and their relationships with solar activity. It was coincident with the scientific and technological advances associated with the USA–USSR 'space race', and many countries around the globe participated. The IGY was extremely successful at achieving international collaboration and stimulating outstanding research. As a result, the idea of having a similar initiative for the life sciences soon arose (Worthington, 1965). The presidents of the ICSU (Peters) and IUBS (Montalenti) started to discuss this idea in 1959 as concern was increasing about human population growth and our relationship with natural and managed systems (Rabinowitch & Hasler, 1965; Fenner & Rees, 1980). The IBP was approved by the ICSU in 1963. In 1964, the first IBP Assembly was held in Paris at which its objectives were defined as: to ensure a world-wide study of (a) organic production on the land, in freshwaters and in the seas, and the potentialities and uses of new as well as of existing natural resources; and (b) human adaptability to changing conditions (Worthington, 1965; Frankel, 1966; Fenner, 2008a,b). The IBP was intended to last longer than the IGY because of the disciplinary complexity involved in environmental research (McKee, 1970).

Figure 1. A timeline of selected global initiatives to facilitate global research collaboration, from the establishment of the International Council of Scientific Unions in 1931 until 1980.



The International Council of Scientific Unions (ICSU, now the International Science Council) hosted the IBP International Committee and the Royal Society agreed to provide space for the Special Committee of the IBP (SCIBP) to provide direction for the program. The IBP ran from 1964 until 1974 (Fenner and Rees, 1980; National Academy of Science: www.nasonline.org/about-nas/history/archives/collections/ibp-1964-1974-1.html#series 1). Despite general recognition that the work planned for the IBP was urgent, there was little money allocated centrally to the research component, with the exception of the organising committee (Frankel, 1966). This greatly limited participation by many countries, including Australia, each country needing to make independent investments to even support their scientists to participate in meetings. This cut across one of the goals of the IBP, which was to strengthen scientific support for developing nations through international collaboration. The United Kingdom, Czechoslovakia, Poland and Japan provided national funds to the initiative, and eventually scientists participated from Iceland, Denmark, the Netherlands, France, Belgium, Italy, the USSR, Thailand, Australia and New Zealand, using varying sources of funding (Coleman, 2010). In 1967, the United States Congress made a substantial commitment of US$50 million to the program, with funding directed at the development of a Biome Studies program and most of the funds administered by the National Science Foundation (Mitchell et al., 1976). The Biome Studies program was unprecedented in scope and greatly inspiring internationally. It advanced ecology as a 'proper' quantitative science with systems ecology as the integrator, which disaffected many ecologists who had until then been largely species focused, but heralded the adoption of a holistic approach to ecosystem studies (Kwa, 1987; Coleman, 2010, Chapter 2; Michener, 2015). It has been hailed as the single most important event in the promotion of systems ecology (Kwa, 1987) and provided the focus for subsequent process-based research (Coleman, 2010).

The IBP initiative produced a large body of output, particularly in the USA which to date has been the most studied of the participating countries (e.g. Mitchell et al., 1976; Kwa, 1987; Coleman, 2010; Michener 2015). Twenty-four IBP Handbooks and 19 Synthesis volumes were produced (Fenner, 1995). The US National Academy of Science holds 7 linear feet of material on the US program alone (http://www.nasonline.org/about-nas/history/archives/collections/ibp-1964-1974-1.html#series%201).

IBP Structure

The IBP was organised into seven scientific areas:

1. PT: Productivity of terrestrial communities.
2. PP: Production processes.
3. CT: Conservation of terrestrial communities.
4. PF: Productivity of freshwater communities.
5. PM: Productivity of marine communities.
6. HA: Human adaptability.
7. UM: Use and management of biological resources (Worthington, 1965).

Each of these sections had an international leader, none of whom were from Australia, but Sir Otto Frankel was on the Science Committee of the IBP and in Australia he chaired the National Committee of the IBP, which itself operated under the aegis of the AAS (Frankel, 1966). In 1964, Ray Specht, who was on a Royal Society-Nuffield fellowship at the University of Oxford, on leave from his position at the University of Melbourne, was invited by Prof. G. E. Blackman (of the University of Oxford and Fellow of the Royal Society) to convene a subcommittee of the international PP Section to work on micro-measurements of the gaseous dynamics of the surface atmosphere.

In Australia it was decided that several sections should be combined: sections 1–3 were assigned to Dr R. L. Specht, as Section PCT: productivity, production processes and conservation of terrestrial communities; sections 4 and 5 were assigned to Dr G. F. Humphrey; section 6 to Prof. R. J. Walsh; and section 7 to Dr O. H. Frankel (Specht, 1966; Humphrey, 1966; Frankel, 1966). There was an overall IBP committee, chaired by Prof. Otto Frankel, with four subcommittees, one for each section (Fenner, 1980). There was no national funding available to support the activities, meaning participation in the IBP had to depend on other sources of funds, such as the Australian Research Grants Council (ARGC), universities and CSIRO, which greatly limited Australian participation (Frankel, 1966; Fenner, 1980). The support of Dr Rutherford

Robertson (then biological secretary of the AAS and Fellow of the Royal Society) and Prof. John Stewart Turner (Fellow of the AAS) was central to the success of the PCT program.

This paper presents some of the outcomes and the major integrating concepts that emerged from the Australian IBP initiative, informed by the personal experience of R. L. Specht. We also reflect on the significance to Australian science of the IBP and similar international initiatives.

The PP and PT Sections

Australian scientists and scientific organisations had much to contribute to the IBP objectives in terms of expertise and activity. In the decade after the Second World War, influenced by the pioneering approach of the Arid Zone Programme of UNESCO, CSIRO Land Research began an integrated survey of the ecosystems of tropical and central Australia (Christian et al., 1954), and also in the Territory of Papua and New Guinea. In 1956, the CSIRO and UNESCO held a symposium in Canberra on Climatology and Microclimatology (UNESCO, 1958). The CSIRO Division of Meteorological Physics was strongly promoting the continuous recording of evapotranspiration, photosynthesis and respiration using meteorological masts above smooth-surface plant communities. The prior experience of Ray Specht (hereinafter RLS) both in Australia and overseas had already convinced him of the potential of the integrated work proposed in the IBP, both in the range of ecosystem components being simultaneously studied and the inter-disciplinary nature of the teams required to do the work, so he was primed to take on the task.

RLS first conducted a survey of Australian PT and PP researchers and found that existing research activity was varied and extensive, making organised re-orientation to adhere to the IBP objectives difficult, especially without any additional funding. Fortunately, however, many existing activities could be linked successfully to the program, and the section committees proceeded to identify priorities for research. For PCT, RLS assembled a committee comprising Ralph Slatyer (photosynthesis), Fraser Bergerson (nitrogen cycling), Tom Neales (pasture structure) and David Angus (meteorological physics) to focus on PP, while Peter Attiwill provided input on themes related to PT. At the instigation of Sir Rutherford Robertson and Sir Fred White (both fellows of the AAS), David Goodall (plant physiology and systems ecology) was brought into the team. At the time, he was at the University of Utah and later became the convenor of the Desert Biome program in the USA.

When RLS was appointed to the Chair of Botany at The University of Queensland in 1966, with the IBP goals in mind and with university start-up funding, he established an integrated research laboratory at the university and obtained equipment for a field installation which after much debate was eventually installed at the Archerfield aerodrome near Brisbane. These facilities were among the most sophisticated in Australia at the time, and RLS was able to recruit new staff of the calibre of David Doley (forest eco-physiology), Colin Field (mangrove eco-physiology), Hal Hatch FRS (of the 'Hatch and Slack' photosynthetic pathway), David Lamb (forest ecology and nutrient cycling), Rod Rogers (lichens and ecology), Ted and Margaret Van Steveninck (plant cellular physiology), Walt Westman (ecology) and David Yates (climate relations in plant communities, *inter alia*). This team and the facilities attracted many international visitors to Brisbane, such as Champ Tanner, Phil Miller, Richard Staff and Peter Day (USA), Bob van den Driessche, Bruce Bohm and Neil Trivett (Canada), Ruhamer Berliner (Israel), Eugene Moll and Fred Kruger (South Africa), Suichi Iwahori (Japan), Margarita Arianoutsou (Greece), Carlos Gracia (Spain), and Arthur Clapham, Chris Page and Tristan Dyer (UK), alongside Australian researchers such as Bill Williams, Fellow of the AAS, who inspired many of the methods used in the CT program, and Catherine Mittelheuser, independent researcher.

A key output of the PP and PT sections was the unique research conducted by Westman and Rogers on North Stradbroke Island, which remains a vitally important piece in quantifying carbon sequestration and nutrient cycling on low-nutrient, freely draining substrates (Westman, 1975, 1978; Rogers & Westman, 1977, 1981; Westman & Rogers, 1977a,b). The work that was stimulated by the PP and PT sections of the IBP in Brisbane and elsewhere in Australia provided a strong legacy that was brought together in the book *Australian Plant Communities: Dynamics of Structure, Growth and Biodiversity* (Specht & Specht, 1999, 2002).

In 1967 when the IBP in the United States received its large grant from the NSF, it also merged its PP, PT and CT sections, and created the Biome Studies program. The Californian sub-committee promoted the Mediterranean Biome Study, firstly between California and Chile, and then worldwide as the MEDECOS (Mediterranean Ecosystem) research study, which held its first meeting in 1971. RLS was closely involved with MEDECOS due to his pre-eminent expertise in heathland ecosystems. Conferences were held biennially, and in 1988 Gideon Orshan (Israel) and RLS (Australia) integrated these studies in *Mediterranean-type Ecosystems: A Data Source Book* (Specht, 1988).

These activities helped RLS to identify a number of basic integrating concepts of community-physiology that guided him in the following decades:

- The conservation of soil moisture.
- The impacts of salt and calcareous dust exposure.
- The survival of heathy vegetation on nutrient-poor soils.
- Soil nitrate production in canopy gaps.
- The alpha and gamma dimensions of biodiversity.
- The relationship between productivity and biodiversity over space and time.

The CT Section

The CT Section was led internationally by Mr Max Nicholson, the eminent conservationist (amongst other achievements, he was a co-founder of the World Wildlife Fund and IUCN). He visited Australia in 1964 to discuss the concept and the plan for each country to collate lists of plant 'communities' for global assessment following a standard procedure, and these would be collated at the Monks Wood Experimental Station in the UK (Robertson, 1974; Clapham, 1980). Subsequently, RLS outlined his proposal for IBP activity in Australia across the PP, PT and CT sections (Specht, 1966). CT became one of the strongest Australian sections, building most successfully on existing capacity and expertise. The Australian Academy of Science established a committee for each state and territory of Australia, including Papua and New Guinea, with support in each jurisdiction. Although the conservation status of fauna was also within the program's scope, it was impossible to pursue this with the lack of funding at the time. It was therefore decided that the focus should be on plant communities, with the knowledge that if a satisfactory plant conservation network could be achieved, most fauna would be protected too (Specht et al., 1974). Migratory animals would require special conservation measures.

The first task was to classify the plant communities in a robust and transparent manner. The international classification of plant communities developed for the IBP (the Fosberg scheme, Peterken, 1967) was found to be unsuitable for Australian conditions, so a new classification based on life form, horizontal cover and height was adopted (Specht, 1970). For many years this was colloquially known as the 'Specht structural formation'. This classification scheme was modified and improved over time (see for example Table 3.2, Specht & Specht, 2002). The novel measurement Foliage Projective Cover, which is an objective point-intercept method, provided a key component of the structural classification (Specht, 1972) and continues to be used in vegetation assessment today, both on-ground and remotely (e.g. Guerin et al., 2017; Fisher et al., 2018).

The largely unfunded efforts of RLS, Ethel Roe and Valerie Boughton (all at The University of Queensland), of each member of the state committees, and of Geoff Mosely of the newly formed (1965) Australian Conservation Foundation, who verified the conservation status of the identified communities, resulted in the publication in 1974 of the Specht Report as a special supplement of the *Australian Journal of Botany* (Specht et al., 1974). This effort broke new ground and provided the basis for the effective conservation of Australian ecosystems (Fenner, 1975).

There were some scientific limitations in the methods used to produce the 1974 report. First, it was recognised that there was little coordination of plant ecological surveys across the continent, resulting in markedly different degrees of resolution and standardisation for comparative purposes. Secondly, the work depended on a committee-based delineation of plant communities, which could result in biased outcomes. Therefore, in the light of greatly enhanced computing capacity in the 1970s and early 1980s, and the sophisticated

classification programs available, RLS determined that the assessment should be repeated, this time using objective methods. With funding from the National Estates Grants Programme (1980–1982), the Australian Biological Resources Study (1980) and a University of Queensland Research Grant (1980–1985) he undertook to:

(i) collate and harmonise all the existing vegetation survey data across Australia;
(ii) convert paper to digital records using the new sophisticated computer systems;
(iii) use the new non-parametric analyses available through CSIRONET[a] to define broad plant formation/vegetation complexes; and
(iv) assess their conservation adequacy.

As described more fully in Specht et al. (1995), 711 ecological surveys incorporating 4088 floristic lists across the continent of Australia were assembled into structural formations and the data entered into the PDP10 computer at The University of Queensland. These large databases were analysed by the polythetic-divisive classificatory program TWINSPAN (Hill et al., 1975; Hill, 1979) on CSIRONET. A total of 343 TWINSPAN Floristic Groups/Subgroups (including 60 understorey subgroups) was defined for the whole continent. A key for identification of each floristic group was created, and using these keys, experts for each community and in each state (often the same people involved in the 1974 assessment) were able to validate the results, and modifications could be made. The floristic groups were then spatially represented and biogeographic regions determined using the classificatory program PATN (Belbin, 1994). The conservation status of each floristic group was assessed using the following criteria:

(i) Is it conserved in a reserve?
(ii) If so, how many reserves and what is the area of each?
(iii) What is the community diversity of each reserve?
(iv) In how many Biogeographic Regions does it occur?

From this it was determined that only 36% of the plant communities in Australia were adequately conserved (Specht et al., 1995).

Separately, a methodology established through the IBP for the determination of conservation areas was applied by Bolton & Specht (1983) and later adapted by Purdie (1987) for the systematic selection of conservation reserves in Australia.

The legacy of the CT work has been further enabled through the advancement of computing capacity in the 21st century, the creation of TRUST-ed repositories (Lin et al., 2020), the world of FAIR (Findable, Accessible, Interoperable and Reproducible; Wilkinson et al., 2016), and open data. In 2018, after a process of data recovery of the digitised records originally collected for the objective assessment (Specht et al., 1995), much of the data so painstakingly assembled was harmonised, the nomenclature and georeferencing brought up to date, and then deposited in open-access, curated repositories (Specht et al., 2018a,b; *Atlas of Living Australia*, https://collections.ala.org.au/public/show/dr8212).

What Came After the IBP?

At an international scale, the IBP was followed by other initiatives, some of which continue to this day (Figure 2). The establishment of the United Nations Environmental Program (UNEP) in 1972 signalled an increasing recognition of the need for a greater focus on environmental matters among governments, and by the 1980s global environmental change, in particular climate change, was increasingly to the fore, and the International Geosphere-Biosphere Programme (IGBP: 1987–2015) was established by the ICSU to "coordinate international research on global-scale and regional-scale interactions between Earth's biological, chemical and physical processes and their interactions with human systems". The IGBP approach was to integrate the Earth's natural physical, chemical and biological cycles and processes and the social and economic dimensions (Kwa, 2005). Although the design incorporated the ecological sciences, its focus on the earth sciences was dominant, not aided by a disjunction in the

[a] An Australia-wide computing network offered by CSIRO (initially through the CSIRO Division of Computing Research) to its staff, government departments, tertiary institutions and private companies between 1970 and approximately 1993 (https://csiropedia.csiro.au/category/history/).

ecological research community which was split between the evolutionary and population ecologists and the systems ecologists, a state of affairs exacerbated by the results of the IBP (Kwa, 1987; Kwa, 2005).

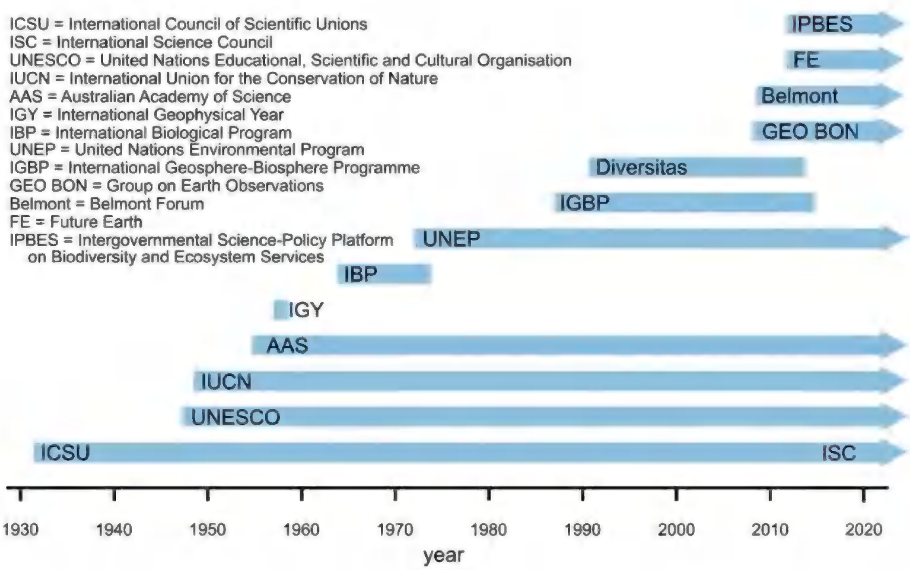
With a feeling that biodiversity was not being well served in the IGBP, the DIVERSITAS program (https://www.diversitas-international.org/) was established (with sponsorship from UNESCO and the IUBS), to develop an international, non-governmental umbrella program for research projects focusing on:

(a) the effects of biodiversity on ecosystem functioning;
(b) the origins, maintenance and loss of biodiversity; and
(c) the systematics, inventory and classification of biodiversity.

This ceased operation in 2014, but not before the Biodiversity Observation Network (GEO BON), a component of the Group on Earth Observations (GEO) with over 70 member countries, was established. The role of GEO BON, consistent with the Convention on Biological Diversity (1992: https://www.cbd.int/convention/), is to collect time series observations of biota and to conduct change assessment in genetics, species and ecosystems, with a specific eye on ecosystem services. The measurement of Essential Biodiversity Variables (Pereira et al., 2013) to enable better detection of important aspects of change is a core component of GEO BON.

In 2009, the Belmont Forum was established, a partnership of funding organisations, international science councils and regional consortia committed to facilitate "international transdisciplinary research providing knowledge for understanding, mitigating and adapting to global environmental change" (https://www.belmontforum.org). A little later, in 2010, a proposal was accepted in response to the findings of the Intergovernmental Panel on Climate Change (IPCC) to establish a science-policy platform on biodiversity and ecosystem services. This resulted, in 2012, in the creation of IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) whose aim is to strengthen the science-policy interface for the conservation and sustainable use of biodiversity, long-term human wellbeing and sustainable development (https://ipbes.net/). It is an independent body under the aegis of UNEP.

Figure 2. A timeline of selected global initiatives to facilitate global collaboration, from the establishment of the International Council of Scientific Unions in 1931 until the time of publication of this article, 2020.



In 2012, the IGBP and DIVERSITAS (https://www.diversitas-international.org/), alongside the International Human Dimension Programme, were forged into one new organisation, Future Earth (https://futureearth.org/), under the governorship of the Belmont Forum, UNESCO, UNEP, ISC, the World Meteorological Organisation and the Science and Technology in Society (STS) Forum. The mission of Future Earth is to "accelerate transformations in global sustainability through research and innovation, focusing on systems-based approaches to improve understanding", which it effects through funding global research projects and various networking initiatives.

Conclusion

This brief, non-exhaustive history of international collaboration in the environmental and biodiversity sciences built around the formation of the IBP illustrates that interdisciplinary international collaboration has long been recognised as fundamental to addressing big ecosystem science questions. Sharing knowledge, technology and expertise is essential for human wellbeing, as well as for conserving and managing our natural resources. Most of the environmental problems and scientific challenges we have faced since the IBP have required considerable international cooperation, which scientists usually initiate individually as far as they are able, as that is their training. At individual level this has, however, always been a struggle. Giving all scientists the opportunity to build meaningful partnerships with their peers and mentors around the world puts Australia on the map, as well as raising the capability of Australian scientists. It is not only bringing new ideas and practices to Australia, it is confirming and communicating Australian excellence as well.

The IBP experience through the PCT program tells us a great deal about the benefits of international scientific collaboration both to individual researchers and to the practice of science. The PCT program, steered by the AAS, was a collaborative exercise at all levels, in particular for the achievement of the CT outcomes. The creation of a new group of high-level scientists supported to conduct top-level science in Queensland – arguably the first time such a concentration of effort had occurred in the state – was greatly stimulated by the existence of the IBP and attracted scientific expertise from around the world, further fertilising the activity. This benefited the training of students, who went on to engage at a higher level than they may have otherwise. It also greatly enhanced The University of Queensland's reputation in the ecosystem and biodiversity sciences internationally.

Australia has been represented on most of the international organisations mentioned in this paper, although not always as a full participant. In many instances the AAS has been the link. Often, Australian representation has been through CSIRO staff. But have these initiatives had wide benefit throughout the research community? Frankel (1966), Fenner & Rees (1995) and Fenner (1995, 2008) repeatedly emphasised that to get full benefit from such initiatives, realistic funding needs to be made available. The outcomes of the Australian PCT section of the IBP would arguably have been much greater if it had not had to rely so very much on voluntary labour and the personal commitment of the scientists involved.

It is comforting to see that one of the main 'new technologies' of the IBP, the systems-based approach, has returned to favour in Future Earth. Equally well, it is encouraging to see that the interdisciplinary and collaborative nature of research proposed by the Arid Zone Research Programme in the early fifties is increasingly being recognised and extended to trans-disciplinary considerations. This brief history shows that environmental and biodiversity science is now regarded as a primary endeavour. One hopes that each new initiative learns from the previous, and that the long-term roles of organisations like the ISC, AAS, UNEP and UNESCO have strong reflective components.

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The Conservation *Atlas of Plant Communities in Australia* (Specht et al., 1995) was launched at Southern Cross University, Lismore, in September that year by Ms Patricia Caswell, the Executive Director of the Australian Conservation Foundation. Pictured at the launch are Elwyn Hegarty and Michael Whelan (back) and Ray Specht, Patricia Caswell and Alison Specht (front).

Author Profiles

Dr Alison Specht has been involved with the IBP project for a long time. As a high school student she spent some holidays entering punch cards into the CSIRONET computer system; while a PhD student at The University of Queensland she entered coded species lists and metadata into the LAN; as a postdoc she ran the project analyses when M. P. Bolton joined the weeds research station in Charters Towers; as an academic at Southern Cross University she was responsible for turning keys into maps for the 1995 *Conservation Atlas*; and most recently she oversaw the capture of data for delivery to open repositories.

Emeritus Prof. Raymond Specht, AO, a member of the Royal Society of Queensland since 1957 and appointed a Life Member in 2015, is an eminent Australian botanist and ecologist. His career accelerated when he was appointed as botanist to the American-Australian Scientific Expedition to Arnhem Land in 1947. This expedition, finally undertaken in 1948, informed much of his later career. He was Professor of Botany at The University of Queensland from 1966 until his retirement in 1989, at which time he was granted emeritus status at the University. He holds a PhD (1953) and DSc (1975) from the University of Adelaide.

Natural Limits to the Expansion of Subtropical Rainforest at Mt Nebo, Queensland

Elwyn E. Hegarty[1]

Abstract

Small patches of rainforest are numerous in subtropical Queensland. Their expansion into adjacent eucalypt forests is limited by fires and other factors. This study was completed in 1980 within a compact site of 200 ha in conserved forest at Mt Nebo, Queensland. It describes the separate contributions of many natural site factors to the stability of the boundaries between these forest types. The survey area included areas of eucalypt forest with a grassy understorey and adjoining ecotonal areas. These, in turn, merged into patches of old-growth complex notophyll vine forest (CNVF). Three separate datasets were recorded from 160 plots, clustered around 32 grid points: (i) canopy species; (ii) woody species in the understorey stratum; and (iii) site characteristics, as indicators of the potential for localised progression from eucalypt to CNVF at canopy level. CSIRO Division of Computing Research in Brisbane processed the data, using methods developed to define initial stages of recovery from clearing inside old-growth CNVF at nearby Mt Glorious. Apart from recent fires, the long-term expansion of CNVF across an ecological gradient at Mt Nebo was limited at various stages by factors such as the orientation, aspect and shape of slopes, soil derivation, the type and thickness of litter cover, soil moisture levels, and the presence and persistence of the exotic shrub lantana (*Lantana camara*). The compact survey area was free of some confounding influences seen in broader regional studies (e.g. variations in elevation, soil derivation, temperature and rainfall, and incomplete records of fire, grazing and clearing). In this study the ranges of separate sets of observations of canopy and understorey trees, and natural site characteristics within each plot, were unusually broad, allowing definition of how natural site factors combine to allow, and limit, succession from eucalypt forest to mature subtropical CNVF in the absence of fire.

Keywords: rainforest, complex notophyll vine forest, eucalypt forest, canopy trees, understorey, history of wildfires, environmental gradients, vegetation succession, exotic *Lantana camara*

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Introduction

The irregular incidence of damaging wildfires can overshadow the influence of the many other natural factors which combine to limit the expansion of small patches of subtropical rainforests in Australia. Localised site factors vary in quality and importance, and may, in favourable conditions, enable the expansion of rainforest into the band (ecotone) which links them to nearby mature forests dominated by eucalypts (*Eucalyptus* spp.), with a flammable understorey of tufted grasses and dry litter. The changing species composition of the understorey tree stratum foreshadows future replacements of species within the associated canopy tree stratum. Over time, the forest structure itself will provide additional factors which can result in a shift of the ecotone linking eucalypt forests and old-growth complex notophyll vine forest (CNVF).

Historical records, based on years of personal observation and forestry experience in regional areas, provide insights into how site factors, including the incidence of wildfires, have influenced

the location of rainforest boundaries in South East Queensland (Tommerup, 1934; Blake, 1941; Webb, 1956; Lahey, 1960; Ridley & Gardner, 1961; Florence, 1965). More recent reports of species groupings and locations in the broad area of the former Brisbane Forest Park (which is now included in the D'Aguilar National Park) include information directly relevant to the smaller Mt Nebo sections of the park (Young, 1982; Noble, 1982).

Several more recent regional studies of Australian rainforest communities have described their distribution and attributes in relation to site factors, such as the incidence of fire and other damage, soils, nutrient levels, climate and altitude (e.g. Russell-Smith et al., 2004; Laidlaw et al., 2011; Laidlaw et al., 2015; Hines et al., 2020). Their conclusions rely on treatments of field data appropriate for particular regions and purposes, but the results of such studies are not always easy to compare directly, even though some similar conclusions may be drawn. Young & McDonald (1987) observed that "given the usual constraints of time and money, it may be that the most meaningful studies of practical value for rainforest conservation are at local and local-regional scales, where plant-to-plant and plant-to-environment relationships can be accurately defined and described using site-specific, quantitative data".

In this study, using records from a compact, intensively sampled site, separate ecological gradients were defined for groups of trees and shrubs in canopy and understorey strata, as well as site characteristics and factors expected to influence the location of the ecotone between eucalypt forest and rainforest (CNVF). Locations of discontinuities between the successional status of existing canopy groups and the understorey species that may replace them were also used to predict where, and why, significant changes to boundaries of canopy associations may be expected in the continuing absence of fire.

Methods

Survey Area

Field observations were conducted in an approximately 200 ha area of conserved subtropical forest adjoining Mt Nebo village. Two former small national parks and small parts of state forest reserves, which constituted the survey site, are now included in the 36,000 ha D'Aguilar National Park. The original walking tracks are still in use and can be used as reference points for locating grid points (Figures 1, 2 and 3).

The mean elevation within the survey site was 469 m (± 41 m). Average annual rainfall recorded in 1980 for the previous 27 years at the nearby Mt Nebo Post Office was 1466 mm. Local records have now been discontinued for many years and the nearest existing stations are not in comparable locations. Rainfall recordings from within forested areas may be complicated by dew and fog, which drip from the canopy to be available within the ground stratum (Specht & Turner, 2006). Timber trees, mostly eucalypts, had formerly been logged in small southern sections (then defined as 'Beauty Spots') of the survey area, but this had already been long discontinued. Routine controlled burning of separate compartments of the former state forest sections of the park were introduced about 11 years earlier, following which none of the survey area, the adjoining Mt Nebo village, or its only public access road, had been affected by wildfires. Previous fires had occurred in the survey area and elsewhere in the former 250 km^2 Brisbane Forest Park in 1936, 1939 and 1957 (Noble, 1982). The Brisbane District Forestry Office provided maps of fire-affected areas in and around the survey area, including where a major fire had burned almost half the site in 1968, but the limited available records of wildfire locations (1951–1968) overlap and were difficult to amalgamate for this study. Areas with no further record of fire between those years are indicated in Figure 2. The most widespread wildfire (1951) had badly affected the survey site and many other sections of local forests, as well as the western edges of the Mt Nebo village. Following the introduction of controlled burns of forests 11 years before this study, there were no further wildfires affecting the immediate local area.

Sampling Methods

Field observations were carried out over 22 days during a relatively dry period in spring 1979. A roughly rectangular set of 32 grid points was set out at 200 m intervals within the site. It was limited in shape by a public road adjoining the park boundary. Grid spacings of 200 m were chosen as the most suitable scale for determining site–species relationships, based on findings by Spenceley (1973). The survey pre-dated GPS technology, so grid points were located by direct measurement with the aid of maps,

clinometer data, aerial photos showing key locations, records of permanent walking tracks, detailed forestry maps and direct measurement (Figures 2 and 3).

Each area of 50 m × 50 m enclosing the 32 grid points contained a cluster of five separated 12.5 m × 12.5 m plots, each set located randomly by compass points around the grid point (inset in Figure 3). Due to some steep slopes (range $<2^0–18^0$) and dense vegetation, grouped plots facilitated access to grid locations to position them and revisit the plots if needed. The total area of plots was 781 m^2, which was approximately 1.25% of the total survey area. The author had managed a family acreage property 1 km from the survey site and was familiar with the local flora. Unfamiliar species were identified with the aid of reference material or by submission of specimens to the Queensland Herbarium. Three separate lists were recorded for each of the 160 plots:

(a) Species and numbers of trees ≥20 cm GBH (girth at breast height) in the upper and lower canopy.
(b) Species and numbers of understorey trees (including shrubs) >1 m tall ("survival level"; Webb, 1956) and GBH <20 cm.
(c) Site characteristics.

Figure 1. General location of the survey area in the D'Aguilar National Park, Mt Nebo, Queensland.

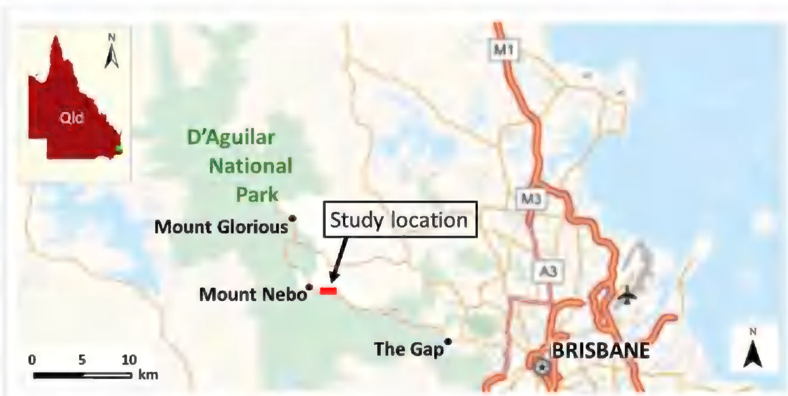


Figure 2. Close-up of the Mt Nebo district where the survey was conducted, showing landmarks, contours, permanent roads and tracks, and limited information about previous fires.

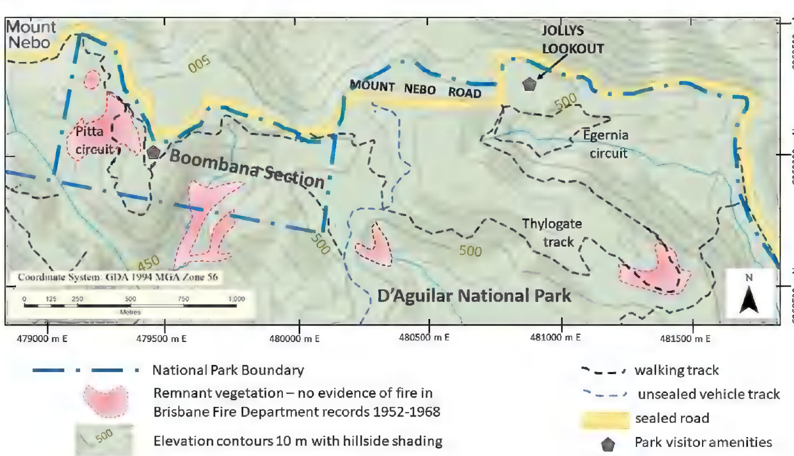
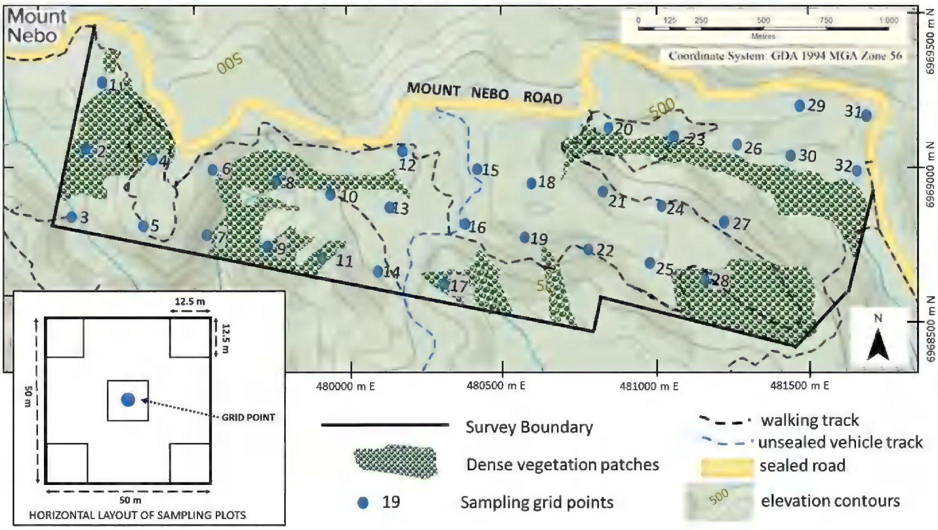


Figure 3. Location of boundaries of survey area, grid points, layout of clustered plots, and approximate areas of denser vegetation, extracted from aerial photos.



Characteristics of the sites were recorded in the following formats:

Presence/Absence

Recent soil disturbance, observed evidence of fire: 0–11 years and older (separately for canopy and understorey trees, as described in the final paragraph below), stony ground >10%, soil moisture above mean level, tufted grasses, ferns (not epiphytic), climbing palms, scrambling vines. buttressed trees, layered canopy with emergent vines.

Numeric

Slope (^{0}), altitude (m), projective foliage cover (%), lantana (vertical leafy branches only), soil pH ($\log_{10}$ value).

Multistate

(5 classes, 25 subclasses of characteristics)

(i) Litter depth: a. ash/bare; b. eucalypt litter <2 cm; c. 2–5 cm; d. >5 cm; e. soft CNVF >5 cm.

(ii) Aspect (^{0}): 0–89, 90–179, 180–269, 270–359, flat (top-slope).

(iii) Surface rock derivation: Granodiorite, hornfels, andesite, recrystallised andesite, altered sediments/conglomerates.

(iv) Slope position: Flat/top, convex, concave, evenly sloping, gully.

(v) Canopy dominants/co-dominants: Eucalypts, eucalypts/brush box (*Lophostemon confertus*), previous group plus CNVF spp., brush box/CNVF, CNVF.

The site factors (a)–(c) listed above were considered most likely to affect the natural progress of succession from understorey to canopy species composition in the absence of fire. While all such factors were included in analytical procedures used during Stages 2 and 3 of the investigation, only those items correlated at high levels with understorey species along an ecological gradient are shown in Stage 4 of the five Stages of the results.

As well as the short period for which official maps of widespread forest fires were available, the maps were also not at a suitably fine scale to be related to the location of the small survey plots. On-site records, included in (c) above, were of persistent evidence of locations of multiple fires over an indeterminate (longer) period than the most recent 11 years, and included trunk damage (e.g. hollowed trunks, charcoal, and recovery by coppicing and suckering rather than by establishment from seed). Figure 2 includes an estimation of

wider areas where fire evidence was not as closely observed during the survey.

Data Treatment

A team of statisticians at the CSIRO Division of Computing Research (Brisbane) had recently used and adapted traditional methods of analysing patterns in forest vegetation and regeneration, enabled by collaborations with plant taxonomists and other expert botanists. Earlier versions of this suite of methods allowed interpretation of subtropical rainforest patterns elsewhere in the region (e.g. Hopkins (1975) in Lamington National Park) and in old-growth CNVF at Mt Glorious, 10 km from Mt Nebo (Williams et al., 1969; Webb et al., 1972; Dale & Williams, 1978).

The group generously transferred information from punched cards (prior to the availability of programs for direct input from large spreadsheets as noted in Table 1). The data were processed using a CYBER 76 computing system and programs from the in-house CSIRO TAXON suite (Dale et al., 1979–1980), to provide all analytical results included in this paper.

The first three stages of analysis described species associations in (1) the canopy and (2) understorey, and (3) associations between the many site factors. Each set of results was then separately ordinated to determine parallel ecological gradients. Stage 4 related the successional associations in the understorey stratum to site factors along an ecological cline, to determine the major factors contributing to the expectation of longer-term change to canopy speciation in the absence of fire. Stage 5 sought to identify areas where there were substantial localised differences between the composition of canopy and understorey strata, and to provide explanations of such patterns.

Table 1. Summary of computing processes used for data analysis in Stages 1–5 of Methods, as documented in Dale et al. (1979–1980) and other authors noted below.

Stages of analysis	Methods and purposes	Where shown in Tables and Figures	Method of input and data processing
1. Canopy trees – coenocline (successional gradient)	ISA (Hill et al., 1975); CANMAR (Lance & Williams, 1967; MULCLAS with flexible classification (Lance & Williams, 1966); GROUPER; Ordination by GOWER (principal coordinates analysis) (PCA; Gower, 1967).	Table 2, Figures 4–5	As available and appropriate in 1980 to the data and purpose of analysis, Stages 1–5. Data was input for processing by a CYBER 76 computing system, using punch cards. This was prior to availability of spreadsheet programs suitable for large data matrices, such as Lotus 1-2-3, EXCEL, SPSS, R, and in-house suites of methods.
2. Understorey trees – coenocline (ecological gradient)	CENPERC3 (classification; based on Shannon diversity; Williams, 1973); CANMAR; GROUPER. Followed by GOWER.	Table 3, Figures 6–7	
3. Site factors (environmental gradient)	CANMAR; MULCLAS with flexible sorting; GROUPER. Followed by GOWER (with centring adjustment).	Figures 8–9	
4. Relation of understorey regeneration and site factors in ecological sequence	Results from 2 and 3 by GOWER followed by CANONGO (Williams & Lance, 1968; Williams, 1976) and principal coordinate analysis (PCA; Gower, 1967; Gittins, 2012) followed by GOWECOR (first 20 Spearman correlations).	Figures 10–11	
5. Identification of areas of greatest potential change to canopy composition	Comparison of separate MULCLAS classifications of 160 survey plots using canopy and understorey data, from Stages 1 and 2.	Based on results from Stages 2 and 4; summary included in text.	

The classifications (dendrograms) from Stages 1–3 were truncated at various levels (6, 7, 12, 25) depending on the scale required to provide and relate separate sets of results from each stage of analysis (1–5) most clearly and effectively, as explained in results. Summaries of the methods and results described above are given in Hegarty (1981) and Clifford & Stephenson (1975).

Results

A total of 141 species of trees was identified in canopy and understorey strata during the survey.

Stage 1: Canopy Trees

Classification

The least abundant canopy tree species, and a further four of unknown taxonomic identity, were excluded from analysis, leaving 94 species. Records from each set of five plots surrounding the 32 grid points were combined for this initial stage of classification because records of canopy-size trees rooted within single plots did not indicate the extent of the canopy cover over individual plots, which extended unevenly across the 50 m × 50 m area surrounding the grid point. Although the classification defined 15 species-groups, as used in subsequent stages of these results, the fusions were truncated at the 10-group level to simplify the constituents of groups involved at each stage, and their subsequent arrangement as an ecological sequence when superimposed on the results of ordination (Figure 4).

Indicator ('leading') species groups were determined by ISA at the simplified 6-group level (4 main groups plus 2 intermediate 'neutral' groups) (Table 2). The results are confined to the indicator ('leading') species (Table 2).

Figure 4. Classification into 10 groups of the combined canopy tree data from clusters of plots associated with 32 grid points (=160 plots), abstracted from the original 15-group fusions.

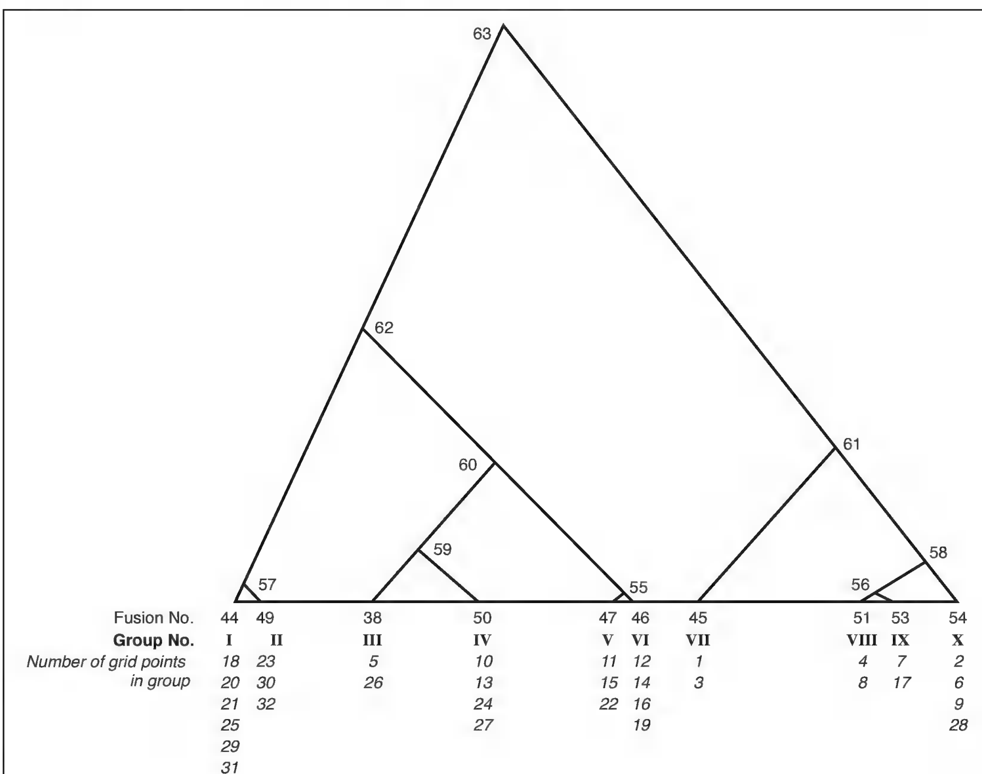


Table 2. Indicator ('leading') and associated canopy species within the Mt Nebo survey site (ISA; Hill et al., 1975).

Group	Leading and associated canopy species
Eucalypt forest:	
Group 1	*Eucalyptus tereticornis* associated with *Callistemon salignus* and *Allocasuarina torulosa*.
	Group 1 merges into Group 2 via intermediate species; *Alphitonia excelsa*, associated with *Eucalyptus acmenoides*, *E. siderophloia*, *Corymbia intermedia*, *E. microcorys*, *E. propinqua* and *Lophostemon confertus*.
Group 2	*Cryptocarya glaucescens*, *Synoum glandulosum*, *Polyscias elegans* and *Duboisia myoporoides*, with *Acacia disparrima*, *Eucalyptus saligna*, *Euroschinus falcatus*, *Guioa semiglauca* and *Trochocarpa laurina*.
Rainforest (vine forest) margins and later stages:	
Group 3	*Acacia maidenii*, *Eucalyptus propinqua*, *Streblus brunonianus* and 30 associated species of eucalypt forest and rainforest, including *Eucalypus acmenoides*, *E. siderophloia* and *E. microcorys*; most other members of the group were more characteristic of rainforest.
	Group 3 merges into Group 4 via 18 intermediate species mostly regarded as rainforest species, but with no *Eucalyptus* spp.; *Lophostemon confertus* and *Synoum glandulosum* (both found widely in the area and included in other groupings).
Group 4	*Cryptocarya macdonaldii*, *Alangium polyosmoides*, and 16 associated rainforest species including *Argyrodendron actinophyllum*, *Sloanea woollsii*, *Syzygium* spp., *Ficus watkinsiana* and remnant *Eucalyptus saligna*.

Ordination

A 15-stage ecological sequence of canopy species-groups was derived, then truncated at the 10-group level as for the classification, and the results were overlaid with the locations of the 10 previously classified groups (Figure 5).

Stage 2: Understorey Trees

Classification

Records for 40 species of which ≤4 individuals were found were not included in further analyses (Figure 6). Data for the remaining 101 species were transformed using $\log_2(n+1)$ to reduce the influence of extreme values while preserving the relationship of intermediate values (Clifford & Stephenson, 1975). The analysis used CENPERC, followed by other procedures (Table 1).

In the final fusion, Groups I–VIII (from the eucalypt forest and ecotone: 116 plots) fused with the remaining groups IX–XV (vine forest stages; 44 plots) at a high level. The earlier of the ecotonal groups (IV–V, 19 plots) had chained to the remainder of groups I–VIII only at the second-highest level.

Figure 5. Ordination of 10 canopy species groups from 32 x 5 clustered plots.

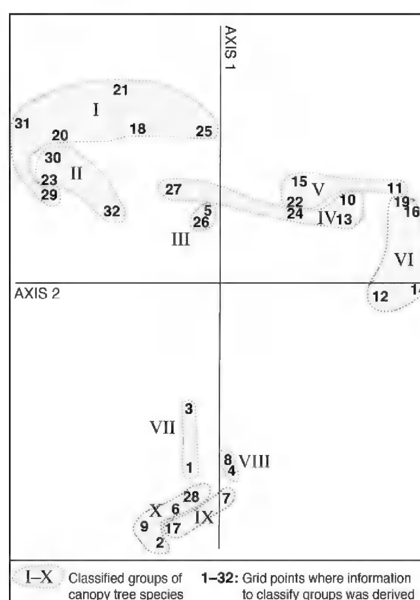
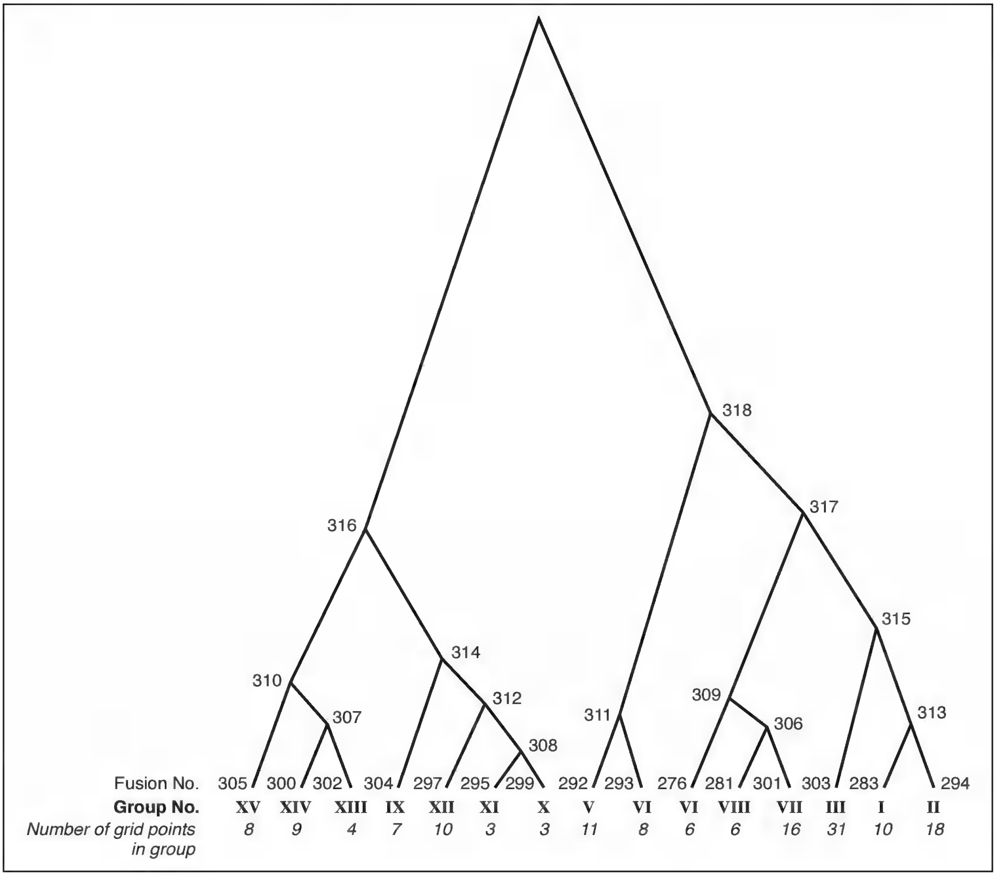


Figure 6. Classification of understorey tree groups from 160 plots showing fusions above the 15-group level.



As all 101 species from 160 plots were used in the classification, only those individual species that were found to be most closely related to particular site factors during succession are included in the results in Stage 5, below. Understorey species diversity increased steadily between Group I (19 species) and Groups IX–XI (78 species), and then decreased to 68 species in Groups XII–XV.

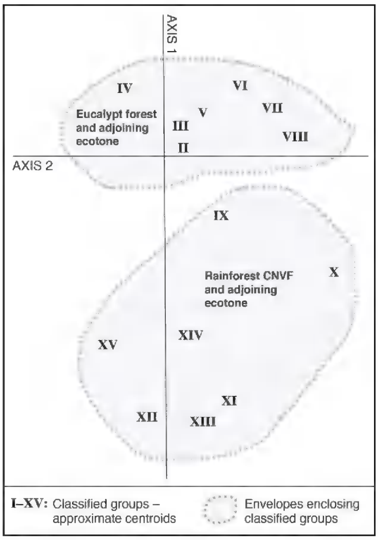
Ordination

Ordination of the understorey tree dataset followed, using GOWER with a centring adjustment (Table 1). The large number (160) of plots in the ordination resulted in overlapping groups of varying size which were difficult to superimpose on the ordination result for Axes 1 and 2. The approximate central points of each classified group could be linked in a continuous line surrounding the intersection of Axes 1 and 2 (Figure 7).

Stage 3: Classification and ordination of plots based on site factors

In the methods used (Table 1), MULCLAS with flexible sorting was "a suitable option for data in multiple states" (Williams, 1973). Groups I–II were clearly distinct from Groups III–XI, with Groups XII–XV forming a separate cluster. Groups IX–XII, the later stages of CNVF-type site characteristics, fused at the highest level. Again, the results were truncated at the 15-group level to facilitate comparison with the results of Stage 2 above and Stage 4 below (Figure 8).

Figure 7. Ordination of 15 classified groups from Figure 6 based on understorey tree data, showing sections of the ecological gradient as discrete groups.



Ordination

An ecological sequence of 15 groups was defined (Method: Table 1), using descriptors of site characteristics from 160 plots. Groups III–XII were very diverse. They had fused early in classification (Figure 9), but a clear ecological sequence was shown by the ordination, and they finally linked to the CNVF groups XIII–XV at a high level. Only 17 plots had evidence of recent fire or surface disturbance (due to maintenance activity), but evidence of past damage by fire alone was observed in canopy tree records for 122 plots and 109 understorey plots. No evidence of fire had been found in 18 plots, all in old-growth CNVF. Forestry maps showing fire locations between 1952 and 1968 for all wildfires had suggested that approximately 128 plots may have been affected.

Stage 4: Relation of Understorey Regeneration and Site Factors in an Ecological Sequence

Previous results in Stages 2 and 3 defined separate ecological sequences for both sets of data, which were then compared by GOWECOR, to show only the higher correlations with the first three axes, providing six sets of relationships. Details regarding the interpretation of the direction of sign in multivariate analyses that involve more than one process are contained in Hegarty (1980) and Dale et al. (1979–1980) (Table 3).

These results are reflected in an illustration of the location of plots where there were close relationships between understorey regeneration and site characteristics (Figure 10).

Group 4 of Figure 10 consisted of only one plot. It adjoined an intermittent stream which traversed Grid Point 22. This result was a possible aberration because the plot adjoined the Thylogale walking track in an area formerly subject to many fires. The leading species identified there – *Eupomatia laurina* (which forms suckers) and *Synoum glandulosum* – are very often closely associated in ecotonal areas throughout the region.

The strongest correlations between the separately classified and ordinated groups of understorey species and site characteristics, over 15 stages of succession, are summarised in a simplified overview of the results of previous analyses (as illustrated in Figures 7–9) in Figure 11.

The inclusion of site descriptors such as layered canopy, canopy height, and the presence of tufted grass and lantana, all of which are associated with potential successional changes of understorey species groups, has allowed the depiction of the ecological gradient between eucalypt forest and vine forest. In the prolonged absence of wildfires in the survey area, Figure 11 indicates the expected limitations to successional change of understorey eucalypt forest towards vine forest.

Stage 5: Species–Site Relationships Between Understorey and Canopy Species-groups, as Indicators of Factors Limiting Boundary Changes

The previous 15-group results of classification and ordination of the 160 plots had used data for trees in the canopy and understorey strata (Figures 5 and 7), The results were also truncated at the simpler 7-group level, at which the series of groups defined were of more approximately equal size in both sets of results. This facilitated direct comparison of the location of each set of plots within the parallel ecoclines (immediately below), which was then followed by comparison of the results with those obtained separately (Figure 10, Stage 4) using PCA to show site factor – understorey species relationships.

Almost half (75) of the plots were similarly placed in both sequences, and about a quarter (42) of the plots were placed only one stage (±) apart, indicating a slow change to canopy structure. The remaining 43 plots were placed at 2–3 stages (±) apart, defining the locations where the greater discontinuity between the composition of canopy and understorey tree strata reflected the higher chance of future expansion of CNVF across the survey site. There were no greater (±) levels of difference than those mentioned.

A difference of +2, in 31 plots, all located within Stages 1–3 of the 7-group comparison, indicated natural limits to the progress of successional change. These were plots with a mostly eucalypt canopy, predominantly seen in plots on drier, exposed sites where understorey change was sometimes impeded by routine clearing of paths and a weedy or grassy understorey. Of the 31 plots, 27 were located in parts of Groups 1–3 of Figure 10, and the remainder were in areas where the plots had been mechanically disturbed.

Differences of –2 or –3 predicted local expansion of existing CNVF patches. Of the eight plots with –2 difference in position on the separately defined ecoclines, seven were in Groups 3–5 of Figure 10, with an outlier in Group 6, being situated in a gully recovering from frequent fires. The remaining four plots (–3 stages of difference) included three which supported persistent lantana clumps, and one (Plot 84) was at a sharp CNVF-eucalypt interface, still recovering from fires.

Within the records of species present at each of the 7 parallel stages, it was also noted that understorey species diversity reached a maximum in ecotonal Group 4, as more CNVF species began to establish, while canopy diversity had increased steadily from 11 to 73 species between Groups 1 and 7 in the parallel set of results.

Figure 8. Classification of 160 plots into 15 groups based on understorey site characteristics.

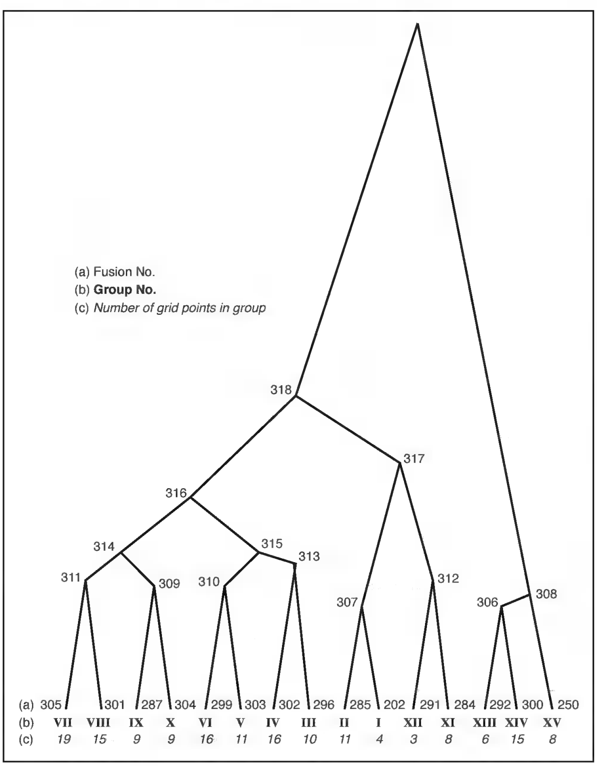


Figure 9. Ordination of classified groups of site characteristics at the 15-group level.

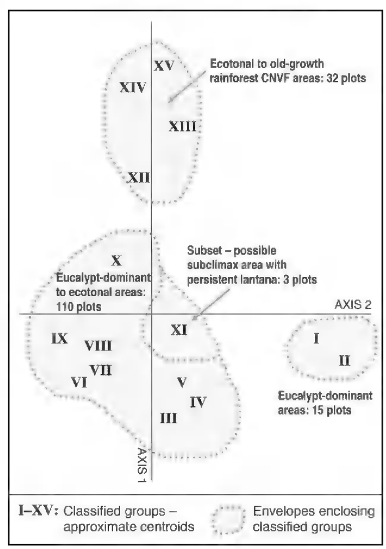


Table 3. Understorey leading species and site (habitat) relationships in the Mt Nebo survey site.

Type	Species recorded	Comments on species-habitat relationships
Type 1 (16 plots)	*Allocasuarina torulosa* *Eucalyptus siderophloia* *Eucalyptus propinqua*	On recently burned sites, grassy but stony, flat uplands; north-easterly convex slopes with eucalypt-dominated canopy. Regeneration of canopy trees at understorey level was very poor. *Allocasuarina torulosa* was marginally most successful. Recently burned sites had also been burned frequently. Low correlations for species indicate very low survival rate of understorey species. Canopy was floristically depleted; no effective regeneration.
Type 2 (6 plots)	*Lophostemon confertus* *Eucalyptus propinqua*	On areas last burned some years previously, with scrambling vines, grasses, deep eucalypt litter and locally dense *Lantana*. Canopy consisted of eucalypts and brush box as co-dominants. Only two species clearly regenerate strongly in this habitat. Other species of this group were less well related to site factors.
Type 3 (12 plots)	*Callistemon salignus* *Denhamia celastroides* *Acalypha nemorum* *Cupaniopsis parvifolia*	On concave, south-east-facing slopes, with soils derived from andesite or basic sedimentary rock, below a semi-open canopy. These species were associated with 14 other species of tree and shrub beneath a rather species-poor sclerophyll canopy, somewhat obscuring the separation of Types 3 and 4.
Type 4 (1 plot)	*Synoum glandulosum* *Eupomatia laurina*	On moister soils on straight mid- or south-west-facing slopes. Hornfels-derived soils, ferny in the understorey, with moderate build-up of eucalypt forest litter. Interpretation of Type 4 was complicated by its single record and its similarity to the next type of association (Type 5), which contained the same species.
Type 5 (15 plots)	*Cryptocarya glaucescens* *Cordyline* spp. *Polyscias elegans* *Guioa semiglauca* *Synoum glandulosum* *Eupomatia laurina* *Archontophoenix cunninghamiana*	On ferny, concave slopes with moist soils. Sclerophyllous upper canopy, with sub-canopy of vine forest species, on hornfels or basic sedimentary rock. All species of Types 4 and 5 regenerate near rainforest margins. Some may persist within rainforest during extended periods of stability (cf. Type 3 species that prefer less-shaded conditions).
Type 6 (30 plots)	*Cleistanthus cunninghamii* *Actephila lindleyi* *Cryptocarya macdonaldii* *Argyrodendron trifoliolatum* *A. actinophyllum* *Alangium polyosmoides*	Tall, layered, closed rainforest canopy, with rainforest litter, lawyer vines and ferns. Relatively high soil moisture, on stony outcrops of basic sedimentary rock. Species are all common to the more mature vine forest understorey. Rarer species were not highly correlated with local site factors (as in previous types). Type 6 combined species of several different associations within the most mature patches of rainforest, although the sample was not large enough to allow further definition of these.

Figure 10. Ecological gradient (six stages) showing the location of 78 plots where the results of ordination of understorey tree species groups and those of site factors were best correlated; 82 plots where the correlations were not as clear are not marked.

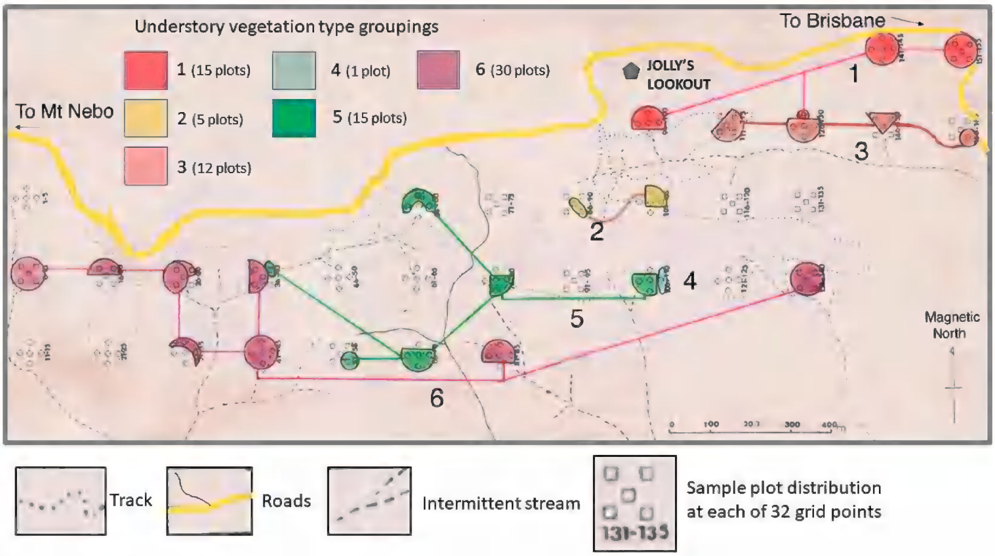
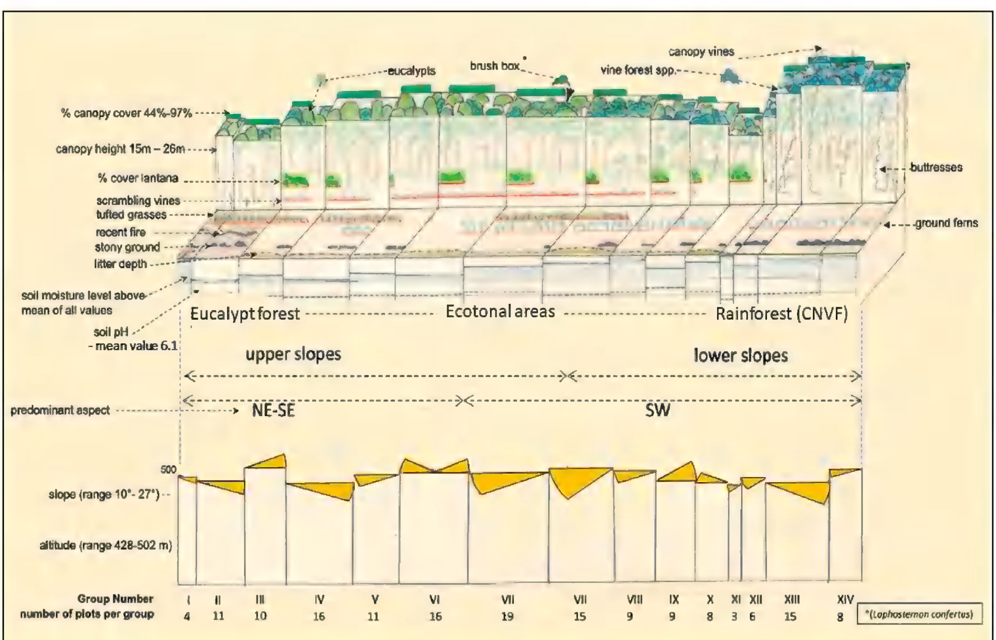


Figure 11. The ecological gradient of relationships between understorey species groups and associated site characteristics.



Discussion

It was opportune that adaptations of existing statistical methods for analysing patterns in vegetation and other data had recently been developed by CSIRO mathematicians in Brisbane. Most of the methods used herein were developed during the previous decade to define stages of CNVF regeneration on recently bulldozed bare basalt-derived krasnozem soils within old-growth rainforest at higher altitude at nearby Mt Glorious (Williams et al., 1969; Webb et al., 1972; Dale & Williams, 1978; Dale, 2000). However, some common canopy-level CNVF species recorded at Mt Glorious are not found in the Mt Nebo district.

Vegetation Patterns

In this study, separate classification and ordination of species composition in canopy and understorey forest strata revealed groups of species associated with eucalyptus forest, and the early stages of establishment of a transition zone, that were clearly separated from vegetation groups where vine forest species were predominant. Studies by Young (1982), Young & McDonald (1987) and many subsequent classifications (e.g. Neldner et al., 2019) have reported similar rainforest species associations in broader landscapes, but they vary between locations due to differences in elevation, rainfall, soils, recent damage and the period of absence of wildfires.

Changing relationships between the distribution of associated understorey species groups and site characteristics along the observed ecocline foreshadow future change to CNVF boundaries (Figures 10 and 11). The initial stages of the 15-part series of understorey species groups from 160 plots were associated with locations on recently burned, mostly convex, north-easterly-sloping ridgetops, on upper and minor slopes, and places often exposed to hot, windy conditions. These sites were situated on drier, locally rocky soils derived from andesite and hornfels, next to a contact zone affected by intrusions of granodiorite, as described by Gradwell (1955). The observation that "Jolly's Lookout soils are inadequate to support rainforest" (Webb, 1956) was essentially confirmed in the present study. Removal of many nutrients from the dry litter and grass understorey by maintenance burning or wildfires, runoff and wind can be expected. Even lantana did not thrive in such sites, although small local thickets had developed opportunistically and persisted nearby, and some scrambling extensions of branches were recorded in a quarter of all sites.

Later stages of the ecocline depicted in Figure 11 were mostly found on infrequently or never burned sites on sedimentary or adjacent altered rocks situated on lower and concave slopes, such as in shady gullies. In these habitats litter build-ups decomposed more rapidly to mulch beneath a developing closed rainforest canopy. Within-site retention of groundwater from rain and fog also leads to the rapid degradation of soft leaf litter, increases local recycling of soil nutrients, and results in the improvement of soil quality. Soil pH values (range 5.9–6.2) were somewhat lower in rainforest patches than earlier in the ecoclinal gradient. Tommerup (1934) had observed that the vine forest ecotone in the nearby Stanley River catchment "tends to build up its own friable soil as the sere develops, both by the addition of organic matter and by root action on the underlying rocks and clay, whereby soil factors are slowly improved by the advance of the forest itself".

In the absence of pre-1951 details of locations of fires, site factors including visible evidence of past fires combined at each stage to direct the shifting location of the interface (ecotone) between eucalypt and vine forest associations.

This study indicates how the several eucalypt tree species of the canopy stratum of ecotonal areas changed almost exclusively to *Eucalyptus saligna*, which increasingly co-existed with the more widespread, earlier-establishing *Lophostemon confertus* (brush box) as canopy species, throughout the ecotone (Figure 11; Table 2). It then became uncommon inside the small old-growth rainforest patches, where the upper stratum was characterised by emergent epiphytic figs, buttressed trees, and the few species of tall vines which are characteristic of such areas (Hegarty, 1988, 1989, 1991). Increasing shade during the development of a layered canopy discouraged regeneration of most weedy species, including lantana, and of small-seeded plants such as tufted grasses. Constant disturbance of the litter layer by foraging birds such as noisy pittas (*Pitta versicolor*) was another deterrent to their germination.

The site–species relationships described above extend and complement information regarding those defined by previous studies across broader landscapes with differing site characteristics, such as those by Laidlaw et al. (2011, 2015) and Hines et al. (2020). Factors such as altitude, soil derivation and climatic variation were more variable in such studies than within the compact, intensively sampled Mt Nebo survey area. The results which appear to be most similar, and comparable in some respects to those of this study, are those from the 500–600 m level of an altitudinal gradient of CNVF in the Lamington region of South East Queensland (Laidlaw et al., 2011). However, the species array and site factors such as soil derivation differ somewhat from those found at Mt Nebo.

Influence of Wildfires on CNVF Succession in the Survey Area

Crown fires, which are the most damaging form of wildfires, are not as frequent in subtropical forests as in temperate regions (Webb, 1968). However, lightning during thunderstorms, which mainly approach Mt Nebo from the south-west, can result in spot, or more extensive, fires.

A long-time Mt Nebo resident, Miss Mary Hall (pers. comm., 1979) recalled seeing open grassland in areas of the village, which had been replaced over 60 years by a mixed community including rainforest species and woody weeds, mostly exotic, with lantana the most widely found. Some evidence of old, unrecorded fires was observed deep in areas that now support mature ('climax') vine forest communities. Aboriginal use of fire in the area has not been well recorded.

Since control burning of forest compartments to the south began about 17 years after the extensive fire of 1951, no wildfires had entered the survey site. In ridgetop areas closest to the southern side of Mt Nebo Road, regeneration from a wildfire in 1968 (which burned about half the survey site) had been increasingly of rainforest species beneath an existing shady rainforest canopy, rather than new establishment of eucalypt species by seed from the adjoining steep north-facing slopes.

Long-term observations of subtropical rainforest regeneration elsewhere, such as those of Lahey (1960), recount the ability of rainforest pioneers to expand the boundaries of their parent community in the absence of fires. Webb (1977) cited work by Hopkins (1975), who summarised rainforest succession in the Lamington area. It was postulated that it would take 15–50 years to form an early secondary canopy, 100 years to an intermediate stage, and 200–300 years to form a very tall, mature canopy including species of *Argyrodendron*, *Syzygium* and *Cryptocarya*, classified in this report (Table 2) as typical of the small patches of old-growth vine forest at Mt Nebo. However, many prominent rainforest canopy species in the Lamington area, at the higher elevations, were not present at Mt Nebo or Mt Glorious.

The failure of regeneration of hoop pines (*Araucaria cunninghamii*) in the survey area, despite several relict specimens in unburned CNVF, and the nearby presence of mature specimens, tends to confirm a very long absence of fire in the oldest CNVF patches. Hoop pine is very sensitive to fire (DAF, 2017). The layout of the grid points in the survey had bypassed the location of a few surviving remnants of a former planting in a grid pattern near the Boombana section. Tommerup (1934) had noted that hoop pines regenerate poorly on the majority of non-rainforest soils, which are "devoid of decaying organic matter". Regarding *Eucalyptus saligna*, almost the only eucalypt which survives as a canopy emergent in Mt Nebo CNVF, a local resident (the late Mr Darcy Kelly) had worked to expand a local private rainforest. He observed (pers. comm., 1979) that it took two years to become established from seed that fell on bare soil, e.g. following a fire, and to rise through and persist above the shrubby lantana, which establishes more quickly on the same sites. In the present study, *E. saligna* was the only local eucalypt found to have established in the ecotone adjoining sclerophyll forest. *E. grandis* occupies a similar position in some nearby forest areas.

Lophostemon confertus (brush box) was another large tree found very widely across the survey area, persisting as an emergent in CNVF. Florence (1965) observed that brush box, being widely tolerant of variable site conditions, can persist in otherwise very adverse habitats, though its ultimate size is a function of habitat factors, including soil fertility. In a study of fire effects in a comparable area of the

Mackay highlands, containing rainforest and scrub (Hines et al., 2020), it was noted that since a catastrophic fire in 2018, there had been little recovery, and extensive lantana invasion. In combination with other factors, lantana was likely to have exacerbated the extent and severity of fire in those areas. It was also noted (loc. cit.) that fire promoted regrowth of *Alphitonia* and *Acacia* species, but not as quickly as lantana, as was also observed during the present study.

Discontinuities in the Progress of CNVF Regeneration

This section identifies locations where understorey species groups indicate future localised change as they replace the canopy directly above. The results complement and reinforce the connection between site factors and understorey composition, as shown in Figure 10.

The combined results of this study indicate a generally slow, orderly progress towards species change in the absence of fire, though this is still limited by site characteristics. Steady progress towards expansion of rainforest margins can be expected to take place over about half of the survey area in the absence of fire. The greatest discontinuities were found within sections of the ecotone which linked eucalypt forest and CNVF, particularly where there were lantana thickets, had been multiple episodes of damage by fires, or were in the vicinity of CNVF, where shade-intolerant species decline. Although the lantana thickets were evidently slowing or preventing regeneration of all competing species, the results do not indicate the full area of lantana presence, as its many thin, opportunistically rooting extensions are usually close to ground strata, and are below the minimum size for understorey recording. The uneven persistence of lantana, considered as a site factor which may inhibit succession in the ecotone bordering developing CNVF, is indicated in Figure 11.

Conclusions

In the absence of fire, site factors combine unequally during succession to inhibit or promote the expansion of rainforest remnant patches. Where rainforest patches are surrounded by flammable eucalypt forests, pattern analysis tools used and developed by CSIRO for prior studies in a nearby larger, old-growth rainforest (CNVF) allowed comparisons of patterns in three independent sets of data from each plot – canopy trees, understorey trees and shrubs, and site characteristics. This has allowed comparison of successional groups of species at canopy and understorey level, and the definition of relationships between understorey speciation and many site factors in an ecological sequence, which defines, and variably limits, the possibility of extension of patches of vine forest during the prolonged absence of fire.

The most relevant factors influencing the possibility of shifts in vine forest boundaries, apart from fire history, included the direction, and particularly the shape, of slopes (ranging from convex to concave), soil moisture and derivation, the height and openness of the canopy, and more recently the presence of opportunistic woody weeds. All of these factors, and others less clearly associated with the predicted change in position of the ecotone, varied in importance along a 15-stage ecological sequence (Figure 11).

It was difficult to compare the results of this intensive local survey with those of more recent studies that vary with regional location, local vegetation composition, the size of areas surveyed, the arrangements of sample plots and locations, the choice of categories of environmental data, and fire history. However, it is expected that the same successional processes and relationships to site factors defined here could be reliably observed in other similar subtropical Australian locations, depending on the combination of natural features of sites. However, the major determinants of the boundaries of subtropical rainforests will inevitably include the continuing absence of fire.

Exotic trees and shrubs were uncommon within the survey area at the time of the study. However, recently naturalised species were present nearby. Some of these, including *Ochna serrulata*, Kahili ginger (*Hedychium gardnerianum*) and privets (*Ligustrum* spp.), are more tolerant of shade during establishment than *Lantana camara*. In the longer term, predicted changes to temperature and rainfall, if not reversed, are also expected to affect the integrity of this and many similar areas of subtropical rainforest.

Acknowledgements

Members of the CSIRO Computing Research section, St Lucia, Queensland, provided considerable technical assistance, advice and information on the interpretation of analytical results. Brisbane District Forestry Office and residents of Mt Nebo and Mt Glorious are thanked for historical fire records. The late Professor H. T. Clifford, Botany Department, University of Queensland, is warmly acknowledged for instruction on the use of methods of pattern analysis, and for acting as an external referee for the thesis on which this paper is based. I thank the late R. S. Dick, my supervisor for the Geography thesis work described in this paper, Dr Bill McDonald for assistance and advice during field observations, and Rosemary Hegarty for technical assistance with the presentation of figures. Reviewers of this paper, and the Royal Society editors in 2019 and 2020, are also thanked for helpful comments and advice through the revision process.

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Author Profile

Elwyn Hegarty is a retired botanist, now living in Armidale, New South Wales. Her return to university studies after a long break had been to undertake the study reported here. This was prompted by a desire to understand and use the complicated processes involved in promoting the expansion of patches of rain-forest on a nearby family farm, so as to increase its protection from possible wildfires. Following this thesis in the Geography Department of The University of Queensland, she was a Ph.D. student of Emeritus Professor Specht and the late Emeritus Professor Clifford in the Botany Department. This subsequent study unexpectedly led to new opportunities that involved diversion from further ecological research into other equally demanding occupations. It has been a pleasure to remember the excitement of research and discovery during the compilation of this report.

The Brisbane Astronomical Society (1896 to 1917), Its Six-inch Refractor, and Key Members Dudley Eglinton and James Park Thomson

Peter E. Anderson[1], and Wayne Orchiston[2,3]

The period between 1890 and 1930 saw a flowering of astronomical endeavour in Queensland and also a drama that ended in the demise of the Brisbane Astronomical Society. One of those involved was Dudley Eglinton, a populariser of astronomy who organised the purchase of a 6-inch refracting telescope and established the Brisbane Astronomical Society in 1896. The other was James Park Thomson who founded the Queensland Branch of the Geographical Society of Australasia (later the Royal Geographical Society of Australasia). His main interest was in geography, but he was also a competent observational astronomer. After the demise of the Brisbane Astronomical Society, Eglinton formed a new Society, the Queensland Popular Science and Art Society, and raised funds to buy a new telescope, but he soon became blind. The new Society appears to have quickly foundered, but within a few years the Astronomical Society of Queensland (1927–1978) was formed as a successor to the Brisbane Astronomical Society and Eglinton was elected a Vice-President. Thomson appears to have played no part in this new Society.

Keywords: Queensland astronomy, Brisbane Astronomical Society, D. Eglinton, J. P. Thomson, F. D. G. Stanley, 6-inch Grubb refractor, Queensland Popular Science and Art Society, 12-inch reflector

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Introduction

This paper describes the lives of the 'key players' involved in the formation and evolution of the Brisbane Astronomical Society, Dudley Eglinton and James Park Thomson, as well as Francis Drummond Greville Stanley, the owner of the 6-inch Grubb refracting telescope that was the *raison d'etre* for the founding of the Society. We then detail the formation, history and demise of the Society, and briefly discuss the subsequent founding of later astronomy-related societies in Brisbane.

At the time, Brisbane was a very fast-growing city (Lawson, 1973). The Moreton Bay settlement was established as a penal colony in 1824, and declared a free settlement in 1842. By 1890 the population of Brisbane had increased to around 85,000 (Figure 1), and it reached 200,000 by 1920 (Queensland Government statistics).

For various reasons, best outlined by Orchiston (1998), in the mid-1890s the time was ripe for the formation of local astronomical societies in Australia. They were formed in Brisbane, Sydney, Melbourne and Adelaide. However, the Brisbane Astronomical Society was the only one restricted to amateur astronomers, given the general lack of government support for professional astronomy in Queensland at this time (Haynes et al., 1993). It was the only one established primarily to prevent a 'large' telescope from leaving a colonial capital – all of the other societies were founded primarily to promote observational astronomy, astronomical education and telescope making (Baracchi, 1914;

Orchiston, 1998, 2003, 2017; Orchiston & Perdrix, 1990, 2002; Waters, 1980).

Dudley Eglinton

Dudley Eglinton (1850–1937) was born in Newcastle-Upon-Tyne, England, on 12 October 1850. He studied at nearby Durham University but left after a year when his parents migrated to Queensland in 1870. He worked as an assistant teacher at Warwick, and then moved to the Church of England School at Toowoomba where he became friends with Dr and Mrs Carr Boyd. The latter pointed out the constellation of Scorpio, thus sparking Eglinton's interest in astronomy. He taught at The Valley Primary School in Brisbane for some months before seeing an advertisement for the position of Secretary at the North Brisbane School of Arts (Cleary, 1967). His application was successful and he held this position from 1874 to 1896. Figure 2 shows the North Brisbane School of Arts building in 1877, three years after Eglinton began working there. He demonstrated administrative acumen, despite his young age and lack of prior experience.

In 1872, there were 16 Schools of Arts in Queensland (Clarke, 1992), and although most merely functioned as libraries and recreational centres, the prevailing view was that they also should be involved in education. Two of the strongest advocates of this philosophy were Charles Lilley (1827–1897) and John Douglas (1828–1904), who supported the cause of technical education at Committee meetings of the Schools of Arts, in public lectures and in articles in the press. They claimed that knowledge was important for its own sake and that it was a source of social and moral benefit. They expounded the liberal faith that education was an essential ingredient of progress. More importantly, they presented the utilitarian viewpoint that technical education provided more efficient and skilled artisans, which was necessary for a society undergoing the initial stages of industrialisation and urbanisation (Clarke, 1992).

Figure 1. A bird's-eye view of Brisbane in 1888 (Source: Museum of Lands, Mapping and Surveying, Brisbane).

Figure 2. The North Brisbane School of Arts, at the corner of Queen and Creek Streets, in 1877. It is the larger of the two buildings (Source: Wikipedia).

The most effective way of achieving this was through formal classes. This eventually led in 1882 to the founding of the Brisbane Technical College affiliated with the North Brisbane School of Arts. By October 1882 the Technical College was offering classes in (i) freehand and mechanical drawing; (ii) geology and mineralogy; (iii) bookkeeping; (iv) French; (v) German; and (vi) the history of the British Empire. Sixty-nine students were enrolled (Clarke, 1992). Eglinton not only played a key role in the development of the North Brisbane School of Arts, but he convinced Douglas that a technical college was viable, wrote an influential pamphlet on technical education, conducted a successful publicity campaign in the press, and put all of his organisational ability into ensuring the success of the college (Clarke, 1992).

During his time as Secretary of the Brisbane School of Arts, Eglinton impressed people with his diligence and courtesy, but troubles lay ahead. In 1891 moves were afoot by dissident Committee members to have the Treasurer, Mr S. W. Brooks (1840–1915), who occupied a senior position at the Brisbane Technical College, replace Eglinton as Secretary. Towards the end of 1891, the Committee terminated Eglinton's appointment because of "inefficiency". This charge was never proven, and it would appear he was 'set up'. The action was controversial and became public knowledge (e.g. Anon., 1892a).

The Half-yearly Report of the Committee and the accounts were to be considered by the members at a meeting a month later on 28 January 1892 (Anon., 1892b; Anon., 1892c). Four or five hundred people were present, including the Mayoress. The meeting was very lively, and when it came to the vote, the Half-yearly Report and the accounts were rejected. The meeting was adjourned – Eglinton had won convincingly.

On 5 March 1892, a newspaper report (Anon., 1892d) described a meeting held on 25 February. Once again there was a large attendance, and Eglinton, as Secretary, stated he had called the meeting under Rule XI after receiving a requisition signed by 20 or 30 members. At the meeting, new office bearers and Committee members were elected by ballot.

Eglinton continued to occupy the position of Secretary until 1896. We have been unable to determine why he chose to leave the North Brisbane School of Arts after more than 20 years, but maybe he tired of the constant challenge to secure funding

from the government and from student enrolments, especially in light of the turbulent economic conditions in Queensland during the depression of the early 1890s. There was also agitation for the government to reform technical education throughout Queensland (Clarke, 1992), and the loss of the Brisbane Technical College and its income stream, once it became an independent entity in 1889, was probably a critical factor (Clarke, 1992). There may also have been continuing friction from the dissident Committee members involved in the infamous '1892 affair'. We surmise that it was a combination of factors that led Dudley Eglinton to resign. He may have reflected that on 12 October 1896 he would turn 46, and it was time for a change while he was still young enough to take on a new challenge.

Dudley Eglinton married twice during these years. He married Eveline Stanley Phelan (1858–1883) on 22 April 1879, but she died from tuberculosis on 18 April 1883, four days before their fourth wedding anniversary. Sadly, she was only in her mid-20s. Four years later, on 11 April 1887, he married Irish-born Martha Shirlow (1861–1919). They had eight children, five of whom survived him. Martha died on 30 October 1919.

Teacher, Writer and Lecturer

A newspaper advertisement dated 24 August 1897 (Anon., 1897) advises "Private School and Evening Classes" at "Concord", Merivale Street, South Brisbane, but it appears that Eglinton moved from these premises, the house being advertised for rent on 11 January 1898 (Anon., 1898). The Post Office record for 1897–1898 also has him at this address. He may have lived on-site with his family. Alternatively, he may have been looking after his ailing father, the Reverend William Eglinton (ca 1818–1898) in Church Street, Toowong, in which case the Merivale Street house was merely a business address. To add further confusion, he is listed at the Church Street address in Australian City Directories for 1894 and 1896.

There is also a reference in the Eglinton family papers to a "… school roll book listing students who attended Dudley Eglinton's private school for youths and young ladies that was located on the corner of Peel and Stanleys [*sic*] Streets, [South Brisbane]". This address is compatible with the Post Office entry for 1901 which describes him as a "teacher". In 1902, Dudley Eglinton's postal address was Ipswich Road, Woolloongabba; then, in 1903, Jeays Street, Bowen Hills; in 1905, Markwell Street, Bowen Hills; and in 1907, Gladstone Road, Highgate Hill. Clearly these were residential addresses.

Apart from his teaching activities, there is no record of later employment except for an intriguing entry in a 1908 list of voters, where a Dudley Eglinton of "Woodhope", Walmsley Street, Kangaroo Point, is shown as a "collector" (employed to collect debts, tickets, taxes, etc.). Postal records also place him at this address between 1908 and 1912. He probably owned the Kangaroo Point property, and in 1912 may have sold it to purchase 'Holly Dean' in River Road, Milton, for £400 (K. Eglinton, n.d.). This large, well-known house (Figure 3), on an acre of ground, first appeared as his residential address in the 1913 Commonwealth electoral roll. Thereafter, he was described on the electoral rolls as a "writer and lecturer", until 1928 when he was listed as a "lecturer".

Emerging Interest in Astronomy

It would seem that Eglinton's interest in astronomy grew through his association with the North Brisbane School of Arts. After his marriage in 1879, he and Eveline lived in Vulture Street, South Brisbane, and on clear nights he liked to examine the sky as he walked home from work (Anon., 1930), at a time when light pollution had yet to become an issue. However, there is no evidence that he observed the 1874 or 1882 transits of Venus, both of which were well publicised (Lomb, 2011; Orchiston, 2004). In 1882, south-eastern Queensland was covered by clouds on the vital day (Orchiston & Darlington, 2017).

In 1912, Eglinton was elected a Fellow of the Royal Astronomical Society (F.R.A.S.), nominated by Colonel E. F. Plant of Brisbane and seconded by Sir Benjamin Stone (1838–1914), a British politician and accomplished photographer. Financial circumstances forced Eglinton to resign in 1928 (Eglinton, 1928). Despite claims made by Orchiston (2017, and in earlier papers), Eglinton does not appear to have had an observatory, or owned an astronomical telescope. This confusion arose because Eglinton was instrumental in obtaining a 12-inch reflector in 1919 (detailed later) and installing it on the roof of the Old Fire Brigade Building; however, he did not

own the instrument. Various directories show him at 10 different Brisbane addresses between 1888 and 1913, and given the frequency that he shifted residences, he could not have maintained an observatory for very long.

Like other amateur astronomers throughout Australia at this time, Eglinton was a populariser (Orchiston, 1991; 1997a), and his dogged determination largely sustained public interest in astronomy in Brisbane from 1896 until 1925, and to some extent thereafter, even though blindness had overtaken him.

The Twilight Years

The cause and date of Eglinton's blindness are uncertain, but family records indicate his sight was almost gone when he visited his son Eric in Toowoomba in 1923, and he certainly was totally blind by mid-1925. It has been claimed that his blindness was due to telescopic observations (Anon., 1937a; Anon., 1937b), but he was an experienced observer so this is unlikely. A medical condition is more likely, particularly as both eyes were affected. It could have been genetic, since at least two of his sons suffered from eyesight problems (K. Eglinton, pers. comm., 2020), but without access to ophthalmic records the cause of Eglinton's blindness remains unknown.

Certainly he was afflicted by 21st July 1925 when a partial eclipse of the Sun visible in Brisbane ended at 7.24 am. Eglinton (1925) stated:

> I should be glad if you would inform your readers that my want of eyesight prevented my seeing more exact particulars concerning the places from which the eclipse would be noticeable. Observations made by a friend at Toowong [7.30 am] … revealed … that the Sun's face was in no way marred by any interposition of the Moon …

When he was already blind, Dudley Eglinton married for the third time, on 4 August 1926 (Figure 4). His bride was Anna Catherine Sophia Nicholson, who was born on 16 January 1861 and was 87 when she died on 16 October 1948, having outlived Eglinton by 11 years.

Figure 3. 'Holly Dean' in River Road, Auchenflower (Source: State Library of Queensland).

Figure 4. The wedding of Dudley Eglinton and Anna Nicholson on 4 August 1926 (Source: Richard Tassicker).

Anna was from a German family living in San Francisco, and was described as an accomplished German and Swedish scholar and translator (Anon., 1905). Her marriage to Eglinton may have been concurrent with or not long after his move to 'Vort Hem' (Swedish for 'Our Home'), in William Street (Wade Street since 1938), Virginia (see Figure 5), where he is recorded on the 1928 and 1934 electoral rolls as a "lecturer".

Despite having lost his eyesight and no longer able to make astronomical observations, in the last decade of his life Dudley still corresponded and wrote articles, dictating to Anna. From various newspaper articles that appeared in both their names (e.g. Eglinton & Aliquae, 1926; Eglinton & Eglinton, 1933) it is clear she also collaborated with him and carried out research. Anna also attended meetings for her husband and even presented a paper to the first meeting of the Amateur Astronomical Society of Queensland on 3 October 1927 (the word 'Amateur' was formally deleted from the Society's name on 4 February 1928). The new Society had two Vice-Presidents, one being Eglinton. By this time he rarely left home, so his election must have been in recognition of his contribution to astronomy in Queensland and for successfully transferring the remaining property of the defunct Brisbane Astronomical Society to the new Society. Well-known local astronomer John Beebe was a Councillor of this new Society, but there was no mention of J. P. Thomson (see later).

In January 1930, a detailed and comprehensive interview on Eglinton's life and achievements was conducted by reporters at his home, indicating he still had complete command of his mental faculties (Anon., 1930). Another report stated: "... that those in his company, whilst engaged in animated conversation, were almost prone to forget that he was totally blind" (Anon., 1937b).

In December 1930 he was represented by Anna at a function for his 80th birthday, his health preventing him from attending. He continued contributing the occasional article to journals and newspapers (e.g. Anon., 1930; Anon., 1937b). In 1935 he was made an Honorary Life Member of the Astronomical Society of Queensland, and his final astronomical article, entitled 'The Southern Cross', was published in the *Queensland Agricultural Journal* in December 1936 (Eglinton, 1936).

Figure 5. 'Vort Hem' in William/Wade Street, Virginia (Google Earth).

Dudley Eglinton died on 10 June 1937 and was survived by his wife Anna, and by three sons and two daughters from his previous marriage.

James Park Thomson

James Park Thomson (1854–1941) (Figure 6) was born in the Shetland Islands, the son of Laurence Thomson, a farmer. At age 18 he went to sea, visiting the United States and South America. Returning to Scotland, he learned the rudiments of marine engineering in Glasgow (Kitson, 1990). In 1876 Thomson visited New Zealand, and from 1877 spent two years working with surveyors in New South Wales. Securing an appointment in Fiji, he was registered as a land surveyor in March 1880.

Thomson was interested in astronomy, and in November 1881 he observed the transit of Mercury from Fiji, and the following year supervised observations of the transit of Venus from Levuka in Fiji (Kitson, 1990). In 1884 he travelled the South Pacific, before joining the Queensland Department of Public Lands in 1885 as a draftsman in the Survey Office. As part of a team, he helped compute the trigonometrical survey of South East Queensland (Kitson & McKay, 2006).

Figure 6. Dr James Park Thomson (after Thomson, 1904: Frontispiece of *Round the World*).

In 1885 Thomson was the driving force behind the formation of the Queensland Branch of the Geographical Society of Australasia (later the Royal Geographical Society of Australasia, hereinafter referred to as the RGSA). He was its honorary Secretary and President (1894–1897) and edited its journal (Kitson, 1990). Throughout his life he maintained a keen 'hands-on' interest in the Society.

Thomson's observations of the transit of Mercury in 1894 (Anon., 1894a; Anon., 1894b) demonstrate his fine scientific approach and thoroughness. He accurately timed this event using Stanley's 6-inch refractor (which is the focus of a later section of this paper) and three carefully calibrated chronometers. He published his observations in the *Monthly Notices of the Royal Astronomical Society* (Thomson, 1895).

Thomson established an observatory at his home, 'Alsatia' in Dornoch Terrace, South Brisbane (West End/Highgate Hill) on the north-west corner of the overpass with Boundary Street. Newspaper reports (Anon., 1899; Anon., 1901a; Anon., 1901b) of his observations of sunspots and comets mention the observatory and an equatorially mounted telescope, but do not provide details. In 1904 or 1905, Thomson left the Dornoch Terrace house. The electoral roll for 1908 has him living at Wood Street, barely 200 metres from his previous residence. It is not known whether the observatory was re-established there.

Thomson was involved in the formation of the Australasian Association for the Advancement of Science (MacLeod, 1988). He wrote more than 200 scientific papers and was instrumental in the adoption of the zonal system for reckoning time in Australia (Kitson, 1990). In 1900 the Queensland Branch of the RGSA named its foundation medal after him (Figure 7), and in 1901 he was its first recipient. Other honours included the Peek Award in 1902 from the Royal Geographical Society (London), and an honorary LL.D. from Queens University in Canada (1903). His book *Round the World* was published in 1904. There were further honours and achievements, including a CBE in 1920. Thomson retired from the Public Service in 1922 but continued to work tirelessly for the Queensland Branch of the RGSA.

After entering the Public Service in 1885, Thomson rose slowly through the ranks of draftsmen until his retirement in 1922. He wasn't listed as heading any specifically tasked Sections, and we venture that he may have been employed on special projects as the occasion arose. For example, in 1909 he successfully identified Burke and Wills' most northerly camp in the Normanton area, Gulf of Carpentaria, and used astronomical observations to determine its position. He published a report on this in the journal of the Queensland Branch of the RGSA (Thomson, 1910).

Thomson was recognised as being an asset to the Survey Office (Kitson, 1990; Kitson & McKay, 2006) and was on good terms with many prominent citizens, probably in part due to his long association with the RGSA.

While living in Australia, James Park Thomson married twice, first to Grace Winter on 20 December 1880, and then, as a widower, to Ada Gannon on 29 June 1887. An accomplished horsewoman, Ada was also involved with the RGSA.

Figure 7. The Royal Geographical Society of Australasia's James Park Thomson Medal, which shows Thomson's likeness. In 1901 he was the first recipient (Source: Museums Victoria).

Later Life

After his retirement in 1922, Thomson seems to have moved at least once. The 1937 electoral roll records James Park Thomson at Wolfdene, via Beenleigh, Queensland. While working for the Lands Department and after retiring, Thomson travelled widely throughout Queensland, lecturing in such places as Charleville, Roma, Longreach, Blackall and Thursday Island. He raised the awareness of local people to their specific environments, while giving them a sense of union with the wider world.

Thomson died at Kilcoy, Queensland, on 10 May 1941 and was cremated. He was survived by his wife

Ada, their three sons and a daughter. Distinguished men wrote laudatory and affectionate tributes, among them Sir Douglas Mawson who extolled Thomson's energy and enthusiasm (Kitson, 1990).

Francis Drummond Greville Stanley and the Six-inch Grubb Refractor

This section deals with the Brisbane amateur astronomer Francis Stanley and his 6-inch telescope, which was to become the central focus of the newly formed Brisbane Astronomical Society. First we provide biographical information about Stanley, and then outline the basics of telescopes and observatories for those without an astronomical background, before describing Stanley's telescope and observatory.

Francis Drummond Greville Stanley (1839–1897) (Figure 8) was born in Edinburgh, Scotland. After studying and practising architecture in Edinburgh, he emigrated to Brisbane in 1861–1862, where he joined the Lands Department. He forged a successful career in the Queensland Government, finally rising to the post of Colonial Architect in 1873, but resigned in 1881 to concentrate on his highly successful private architectural practice.

Figure 8. Colonial Architect Francis Drummond Greville Stanley (Source: State Library of Queensland).

Stanley became the first President of the Queensland Institute of Architects in 1888. He was hard hit by the recession of the early 1890s and was forced into liquidation in 1895. The contents of his house and his observatory were to be auctioned on 30 April 1896, but he was able to retain the house itself. That same year he rejoined the Queensland Public Works Department as a temporary Inspector of Works. The following year he caught a chill at work, and three weeks later, on 26 May 1897, he died of pneumonia (Dictionary of Scottish Architects: Architect Biography report). His widow died in 1921. Throughout Queensland there are many buildings he designed: currently, nearly a dozen have heritage listings.

Telescopes and Observatories: An Introduction to the Terminology

There are two basic types of astronomical telescopes: reflectors and refractors. Refractors are of the 'spyglass' variety, with the main lens (called the objective) at the upper end and the eyepiece at the lower end of the tube. The resolution and light-gathering capacity of a telescope are proportional to the diameter of the main lens. For example, Francis Stanley's refractor had an objective 6 inches in diameter, which at the time was a very respectable size for a refractor owned by an amateur astronomer (Orchiston, 1997b). The most basic type of reflecting telescope – the Newtonian – employs a mirror which is located at the base of the tube, and the focus is commonly brought to the side of the upper end of the tube by a small, centrally placed diagonal mirror. The mirrors in reflecting telescopes often are much larger than the objectives in refracting telescopes. A reflecting telescope with a primary mirror 12 inches in diameter was associated with Dudley Eglinton. It is discussed later in this paper. At the time Eglinton and Thomson were active in Queensland astronomy, there were comparatively few amateur-owned reflecting telescopes in Australia with mirrors in excess of 12 inches in diameter (Orchiston & Bembrick, 1995), and we are not aware of any in Queensland.

Larger amateur-owned telescopes, be they reflectors or refractors, typically were not mobile and needed to be permanently mounted, preferably in an observatory. A hemispherical dome with an opening slot, or a building with a roll-off roof, enabled

the telescope to access most areas of the sky. Within the observatory, the telescope was supported by a mounting, often with a clockwork or motor mechanism (a 'drive' or 'clock-drive'), that compensated for the rotation of the Earth and ensured the object being observed remained in the field of view without the need for continual manual adjustment.

Another type of telescope common during the nineteenth and early twentieth centuries was the transit telescope, which was vital for establishing and maintaining an accurate time service. The transit instrument, nearly always a small refractor, was set in a mount carefully aligned so motion was only possible on one axis, from the northern horizon, through the zenith (directly overhead) and down to the southern horizon. The eyepiece contained one or more crosshairs so that the image of the target star could be accurately timed as it drifted across the meridian. To access the sky, a transit telescope only required a north–south slit in the roof of the observatory, directly above the transit instrument.

Six-inch Grubb Refractor

According to Holmes & Moy (1994) and Orchiston (1997b), Stanley's 6-inch telescope was built by Grubb, a famous telescope-manufacturing firm in Dublin (Ireland) in 1884 after being ordered by J. W. Sutton (ca 1844–1914) of Brisbane. Sutton was the owner of the Kangaroo Point Iron Works and, among other enterprises, was involved in shipping. He ordered the telescope on behalf of a client, John Potts, who paid £180 for it landed in Brisbane (White, 1921).

Potts (1828–1905) lived in Vulture Street, South Brisbane, and has been described as a scrivener (a professional or public writer, notary, etc.). He was also a successful land developer (Brown, 2017), sometimes in conjunction with his son 'Johnny', who in Anon. (1888) is described as a conveyancer. Not very long afterwards, Potts sold the telescope to Francis Stanley for £90, but only after he had already gone to the trouble and expense of building or starting to build an observatory for it. This loss of £90 in the purchase price would not have been large for Potts during the Brisbane land boom of the late 1880s (Brown, 2017).

Mr C. J. White, the Lecturer in Charge of the Sydney Teachers' College, appears to have been the intermediary in this and other Queensland telescope sales. Potts told White that his son Johnny had fallen in love with a girl he did not approve of, and that: "If Johnny takes a liking to an Earthly Venus I do not approve of, he shall never see the heavenly Venus through my telescope" (White, 1921). John William Potts married Ethel Sarah Harcourt on 11 June 1888 and never did get to see the heavenly Venus. True to his word, Potts senior sold the telescope to Stanley.

Due to the financial depression of the early 1890s, Potts' residence, 'Chorlton Villa', was advertised for sale by the mortgagee in 1892 (Anon., 1892e). The description of the property also mentioned: "On a slightly-raised terrace, within a few yards of the veranda, a superb Marble Fountain with Large Masonry Basin and Base …" It appears that the foundations of Potts' observatory had been converted into a fountain. In later years it was described as a 10′8″ (3.25 metre) diameter fishpond (Steve Hutcheon, pers. comm., February 2019). This was a good, elevated observatory site close to the house. Potts sold the telescope before the 1892 mortgagee sale, since it was not on the list of Potts' assets when his property was liquidated.

Stanley installed the 6-inch Grubb refractor in a square observatory with a roll-off roof near his ridge-top home 'Ardencraig' at Toowong (on the corner of Jephson and Golding Streets, using the present-day street names). Subsequently, Thomson (1895) published a description of the telescope. It was:

> …. an equatorially mounted refracting telescope, 6 foot focal length, with object glass 6 inches in diameter, built by Sir Howard Grubb in 1884. It is the property of Mr. F.D.G. Stanley, F.R.I.B.A. The telescope rests on a hollow cast-iron column, 5 feet 9 inches in height and 18 inches diameter at the base, in which is placed the driving clock. The whole metal work is mounted on a stone and concrete foundation carried down to the solid rock 6 feet below the surface of the ground, perfect freedom from vibration being thereby secured.
>
> The observatory … is a wooden building 12 feet square with roof arranged so as to roll entirely off on a railway and framing built to receive it. There can be no doubt whatever that,

> in a fine climate, this arrangement possesses many advantages to which I shall refer later on.
>
> Included in the equipment of the observatory is a transit instrument, by Carl Bamberg, of Berlin (1879). This is placed upon a stone pedestal …

The transit telescope was on loan from the Queensland Survey Office, and after Stanley's death it was returned to them (W. Kitson, pers. comm., 2020).

To place Stanley's 6-inch telescope in perspective, in November 1894 it was the equal-largest refracting telescope in Queensland. The late Edwin Norris (1829–1892) of Townsville and J. Ewen Davidson (1841–1923) of Branscombe (near Mackay) also had 6-inch Cooke refractors housed in observatories (see Orchiston & Darlington, 2017). Davidson's telescope returned to England in 1900 when he retired, but the other two 6-inch telescopes were only surpassed in aperture in 1918 when Dr W. E. McFarlane (1866–1919) purchased a 7-inch Cooke refractor that he installed in an observatory at Irvinebank a tin-mining town on the Atherton Tableland (Orchiston, 1985, 1997b). At a national level, in 1894 the only larger operational refractor owned by an Australian amateur astronomer was the 8-inch Grubb in John Tebbutt's Windsor Observatory, near Sydney (Orchiston, 2017). At this time, of all Australian astronomers, amateur and professional, Tebbutt had by far the most impressive international record when it came to publications and research (Orchiston, 2017), and his telescope also was significantly larger than Stanley's, so we cannot use him as the obvious 'role model' for Stanley. Nonetheless, a 6-inch refractor was capable of doing good work if placed in the right hands, and Davidson, for one, was able to demonstrate this (Orchiston & Darlington, 2017).

Thus, Stanley's Grubb telescope was capable of serious research, but the critical factor was the presence of an astronomer who could identify and successfully activate and lead a research agenda. This would prove the greatest challenge when the Stanley telescope was acquired by the fledgling Brisbane Astronomical Society, but a further factor would be the changing nature of astronomical research world-wide. Consequently: "With the emergence of astrophysics and the international decline of positional astronomy, refractors of extremely modest aperture – by world standards – were no longer capable of contributing to astronomy in the same way that they had done during the nineteenth century" (Orchiston, 1997b).

The Brisbane Astronomical Society (BAS)

When Stanley's possessions were to be seized by his bank, he wanted the telescope to remain in Queensland. He offered to partially fund its purchase by a group of interested residents rather than see it possibly leave Queensland. Therefore, the telescope was not part of the auction.

At a meeting on 5 June 1896 at the North Brisbane School of Arts, an astronomical society was established to purchase Stanley's 6-inch Grubb telescope from Isles, Love & Co for £70. The 76 people who attended formed a Society of Ownership, each paying a "subscription" of £1.

Stanley contributed £20 towards the purchase of the telescope and consented to members using his observatory. The meeting decided the telescope would be used to stimulate interest in astronomy, and conjointly for scientific and general purposes. With the election of three trustees (J. P. Thomson, J. W. Sutton and W. Heath), five councillors and the 68 members, a Society of Ownership, the Brisbane Astronomical Society (henceforth BAS), was declared to be in existence (Page, 1959). F. D. G. Stanley became an honorary member, and Dudley Eglinton was elected Secretary.

The funding was on the basis of "personal debentures". Debentures usually indicate a fixed interest investment, but in this case the word was undoubtedly used to acknowledge a debt that may be repaid upon an event occurring at a later time. Such an event would certainly be the sale of the telescope, which occurred more than 20 years later, in 1917.

The Society had great plans, but they needed: a permanent site for the telescope; to decide who was authorised to operate it; to determine the rights of existing debenture holders versus new members (if allowed); and to resolve other ownership issues. These were discussed at a Council Meeting and at the following General Meeting on 7 August 1896, chaired by J. P. Thomson (Page, 1959). In retrospect, none of these issues was ever properly addressed.

One of the trustees, solicitor W. Heath, F.R.A.S., was an active observer, and with assistance from

J. A. Wheeler, carried out observations with the telescope to determine the latitude and longitude of the observatory. In the process they noticed there was a problem with the clock-drive, and at their 24 September 1896 meeting, the BAS Council authorised maintenance work by Mr A. Herga, a Brisbane watchmaker (Anon., 1896). Council also discussed the use of the telescope and the establishment of different sections to carry out distinct branches of astronomical work. Page (1959) elaborates on this:

> Following the establishment of the Brisbane Astronomical Society … proposals for the formation of a [*sic*] Meteor, Lunar, Solar, Planetary and Double Star sections were put forward. From a study of records available, it would appear that membership response to these proposals was shockingly poor and eventually little work in any one of these fields was accomplished.

Meanwhile, the BAS was concerned that the Queensland National Bank (which had sold Stanley's belongings) could at any time take possession of, or call for the removal of, the observatory. Following lengthy debate at a meeting of the BAS, Thomson moved that the telescope be handed over to the Royal Geographical Society of Australasia, Queensland Branch (of which he was President), with access provided to BAS members. This motion was carried in Eglinton's absence, but at an emergency meeting that he arranged soon afterwards, the motion was quashed and Eglinton successfully gained the necessary support to retain the instrument within the BAS. He also proposed raising £100 for the removal of the telescope from Stanley's observatory and its erection at a new site, but this did not occur and the telescope remained in Stanley's observatory. Fortunately, it appears the bank was not interested in claiming the observatory.

The first Annual Report of the Society on 6 August 1897 stated: "… in the twelve months of existence, the society can scarcely be said to have done anything." Page (1959) has suggested that the lack of leadership within the BAS at this time can partly be attributed to Stanley's death on 26 May 1897, but we have already seen competition emerging between Eglinton and Thomson. Both were capable, strong-willed men and 'key players' in the BAS, and they had already clashed over the issue of telescope ownership. It would seem that they had different agendas and different astronomical objectives for the BAS: Eglinton was a teacher and an administrator and was committed to popularising astronomy; while Thomson, an experienced astronomical observer, recognised the potential of the 6-inch Grubb telescope and undoubtedly was inspired by what was occurring at the time in the dynamic Sydney amateur astronomical community (Orchiston, 2017). The Brisbane scene frustrated him: Brisbane lacked a Tebbutt (Orchiston, 2017), an Innes (Orchiston, 2015), a Merfield (ibid.), or any other prominent amateur astronomer with an international reputation to serve as a role model for those interested in observational astronomy.

Thomson was a pragmatic man. He realised that while some BAS members were genuinely interested in astronomy, others were prominent citizens who had contributed their £1 as a civic duty to keep the Grubb refractor in Brisbane, but they had no interest in research astronomy or in using the instrument. In a letter to John Tebbutt dated 6 June 1897, Thomson lamented that: "There is no room for such an institution [i.e. the BAS] here. Fifty years hence will no doubt be time enough for such a society" (Thomson, 1897).

In 1895 Thomson had delivered some astronomical lectures at the South Brisbane Technical College (Orchiston, 1997a) that may have stimulated Eglinton into doing likewise (ibid.). By April 1900 he had delivered seven public lectures that caused a resurgence of interest in the BAS and also raised funds. But this was short lived and only 10 people paid their annual subscriptions (Page, 1959), some maybe believing their original payment for the purchase of the telescope fully covered their obligations.

Some BAS members observed an occultation of Jupiter on 29 September 1900, but one year later only five members paid their dues and no meetings were held after the fifth Annual General Meeting on 3 October 1901 (ibid.). Eglinton continued to use the telescope for public demonstrations (Skertchly, 1905).

On 30 September 1911, a special telescope owners meeting was convened to determine the fate of the 6-inch Grubb refractor. It was claimed at one point that it was now useless for astronomical work. Cowley (1911) suggested it be donated to

The University of Queensland, but as Secretary of the BAS, Eglinton argued that the original purpose in purchasing the telescope was to prevent its removal from Ardencraig (Page, 1959). However, the real objective had been to keep the telescope in Brisbane, but not necessarily in Stanley's observatory. Members at the 1911 meeting suggested moving the telescope to a more central location, at Highgate Hill (ibid.). Currently, there is a high park with a fine vista, located at the corner of Dornoch Terrace and Hampstead Road, but whether or not this was the site suggested back in 1911 is unknown.

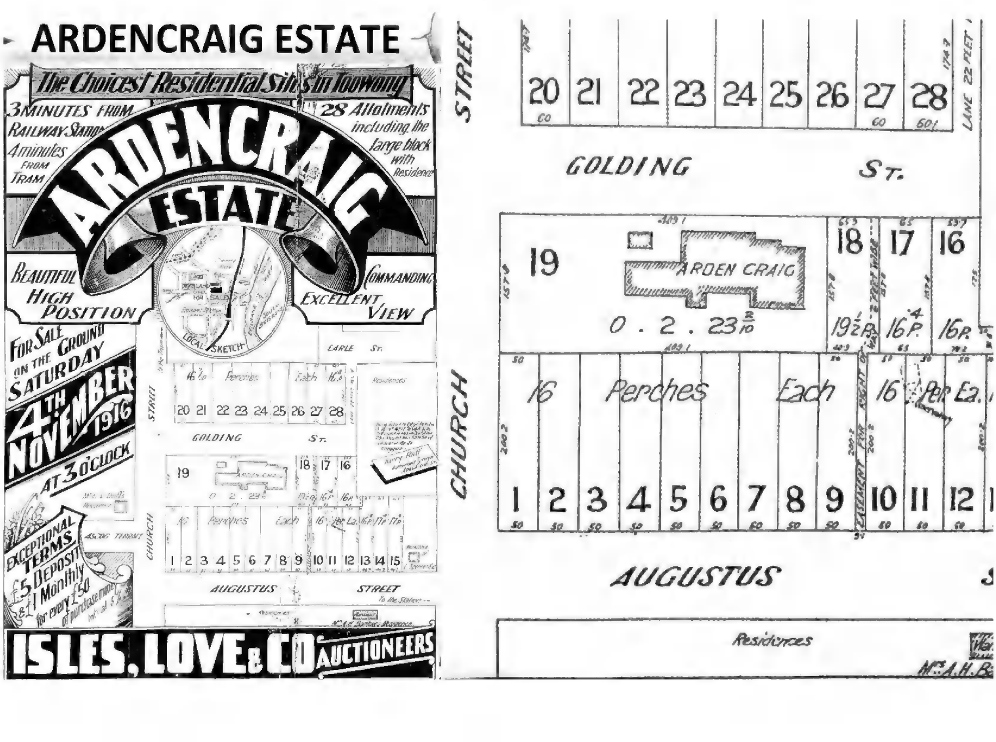
However, despite approaches to local Councils for support, nothing transpired, and Eglinton continued to run his public demonstrations at the same old address, using the Grubb telescope (Anon., 1915). By mid-1915 Australia was immersed in World War I, and these public astronomy nights were in support of the Belgian Relief Fund (Page, 1959). Money collected was donated through *The Brisbane Courier* by F. R. MacDonnell, the new owner of Ardencraig, who was in residence by April 1915. Obviously, the telescope was in an operable condition at this time, as it was on 30 July 1916 that Eglinton and others viewed a partial solar eclipse (Anon., 1916a).

The telescope had remained in its original observatory for 20 years since the Brisbane Astronomical Society acquired it in 1896, and apparently no serious attempt had been made to relocate it. The Society had become moribund. Meetings were no longer held or subscriptions paid, and only Eglinton continued to use the telescope. Events were to take a dramatic turn.

Removal of the Grubb Six-inch Refractor from Ardencraig

Mr MacDonnell, who had bought Ardencraig, decided to subdivide the estate (see Figure 9), and on 7 October 1916 he advertised it for sale (Anon., 1916b). Although the auction was to be held on 4 November 1916, viewing nights with the telescope continued for a short while (Anon., 1916c).

Figure 9. The 1916 subdivision of Ardencraig estate, including a close-up of the location of the observatory (Source: Marilyn England).



A notice appeared in *The Daily Mail* (Brisbane) of 3 November 1916 regarding the auction the following day, The worrying aspect of this notice stated:

> There has been a good demand for plans and buyers are reminded that the sale commences at 3 p.m. sharp with the buildings for removal and the galvanised iron, to be followed immediately by the sale of the allotments (Anon., 1916d).

In the subdivision plan, the observatory building and roll-off roof straddled Lot Nos. 10 and 11 (shown in the right-hand side of Figure 9).

On 4 November 1916, a notice appeared in *The Brisbane Courier*: "Owing to the sale of land at Ardencraig to-day, the Astronomical Society's telescope will not be available to visitors until further notice" (Anon., 1916e). Arthur Page states that the public nights were:

> … abruptly terminated by Thomson, acting now as sole trustee, who "surreptitiously" removed the objective from the telescope … on the pretext that the sale of Ardencraig jeopardised the safety of the instrument, and with that action, the Brisbane Astronomical Society walked out of existence (Page, 1959).

But since Page carried out his research, historical newspapers have become readily available via Trove, revealing much additional information. For example, the following long article dated 21 March 1917 in *The Brisbane Courier* describes the actual sequence of events:

> **The Ardencraig Telescope.**
> More than ordinary interest attaches to the announcement of the sale in Brisbane next Saturday of a telescope. This is the instrument which has for many years been the property of the Brisbane Astronomical Society … As Mr. Stanley, the then vendor, still lived at Ardencraig, the telescope was not removed, and Mr Stanley permitted the new owners to use his well-adapted observatory … When the property was sold to Mr. Francis MacDonnell, that gentleman allowed the telescope to remain on the payment of a nominal sum for security, and proposed an arrangement by which it was used in aid of the "Courier" Patriotic Funds (which benefited to the extent of over £25) till the land on which it was situated was again sold. Prior to the sale Mr. J. P. Thomson, acting in his capacity as sole remaining trustee, without the knowledge of Mr. Eglinton, who had virtually been custodian of the instrument for many years, took possession of the telescope "for safety." A meeting of the shareholders of the society was subsequently held, and it was decided to sell it, Dr. Taylor [1840–1927; Chairman of the BAS] and Messrs. Eglinton and Thomson being appointed trustees with power to sell the telescope, which is now in the hands of the auctioneer. Mr. Eglinton does not concur in the proposal to sell, but has been overruled. Some of the surviving shareholders have assigned their interests in the telescope to Mr. Eglinton, and as that gentleman has in the past done much to promote the study of astronomy locally, it is hoped that he will be put in a position to secure the telescope and continue his work (Anon., 1917b).

The following day, a long letter in *The Brisbane Courier* from Dr W. F. Taylor advised:

> … that at the last annual meeting of the members of the Astronomical Society, Brisbane, held about 10 or 12 years ago, he was elected chairman and Mr. D. Eglinton secretary, and they remained in office until November 24 last, because all attempts to hold meetings of the members proved futile. During that time Mr. Eglinton assumed charge of the telescope, and kept possession of the key of the house in which it was erected, but he consulted the chairman of the society (Dr. Taylor) on all matters requiring decided action. On October 27, 1916, Dr. Taylor had brought under his notice an advertisement for the sale of the Ardencraig land, on November 4, 1916. He saw that prompt action should be taken to protect the telescope, and started to ring Mr. Eglinton on the telephone, but found that he would not be at his residence … Then he got into touch with Dr. Thomson, the only remaining trustee of the telescope who at once consulted his solicitor, and was advised to take immediate possession of the telescope, for when the land on which it stood was sold, the purchaser might raise some objection to anyone removing it. He (Dr. Taylor) thereupon

urged Dr. Thomson to act on his solicitor's advice, and get possession of the instrument as soon as possible. At a meeting of the members of the Astronomical Society, on November 24, 1916, the subject was fully discussed and the following resolutions adopted :—"That this meeting confirms the action of Dr. Thomson in removing the telescope under the circumstances of the sale of the site." Mr. Eglinton and Dr. Taylor having been appointed trustees to act in conjunction with Dr. Thomson, the following resolution was adopted :—"That the trustees be empowered to sell the telescope after advertisement to the highest bidder." This resolution was confirmed at the subsequent meeting of the members of the society on February 26, 1917. In conformity with the above, the trustees decided to place the telescope in the hands of Mr. A. S. Phillips, auctioneer, Queen-street, for sale, and sent him a letter of authority which all three signed (Taylor, 1917).

Then, in a letter printed immediately below Dr Taylor's letter, Mr MacDonnell, the owner of the land wrote:

> Sir,—In your paragraph this morning concerning the Ardencraig telescope there are one or two sentences which may cause a wrong impression, and lead the public to think that I derived some pecuniary benefit from the money subscribed towards the "Courier" Patriotic Funds, which Mr. Eglinton and I collected at the observatory in 1915 and 1916 … In April 1915, after I had come to live here, it occurred to me that the telescope … might be used to … benefit some of the funds which were then afoot. I consulted Mr. Eglinton, and he very enthusiastically approved my suggestion. He offered to pay me rent, but I agreed to allow it to remain rent-free while the war lasted, provided that the proceeds were to be devoted to the purpose indicated above. We agreed that he should pay a small sum, and that it should be one penny per month during the continuance of the war. This we considered sufficient to establish the relationship of landlord and tenant between us … With regard to the telescope being removed "for safety," I may state that whilst being housed here, it could not have been safer in the Bank of England. It was in a strong wooden structure, roofed with iron, and under lock and key. With its removal I had nothing to do. Had it been allowed to remain, Mr. Eglinton, I am sure, would have been only too glad to continue as before, during the war. Very few know except myself, the number of dreary nights he spent there in the dark, waiting for the patrons who failed to come, whilst I sat outside under the shelter of a friendly bush or tree to look after the signal lights, and guide the visitors to the observatory (MacDonnell, 1917).

MacDonnell's letter ignores the legal position when the land the observatory stood on was sold. MacDonnell was responsible for this situation, but maybe wanted to justify his position. From the letters there seems to have been a certain amount of controversy.

Why was the telescope removed and sold? The immediate impetus was the sale of the land on which it was situated, but more importantly, the Brisbane Astronomical Society had ceased to operate. In the 20 years since they acquired the telescope, the only person who regularly used it was Eglinton, and the BAS had not found a new home for it after the sale of Ardencraig. The obvious and sensible action was to sell the telescope and remove this continuing burden. Thomson seems to have been a pragmatic man, and just the person to do this. Whether he removed the whole telescope or just the objective, as Page (1959) states, it set the steps in motion, and it is now obvious that this was carried out under the proper authority and subsequently ratified by a meeting of the Society.

Page (ibid.) refers to the telescope as missing and that the Society formed in 1927 (its name soon changed to the Astronomical Society of Queensland) had a claim to it because Eglinton (now a Vice-President of the new body) managed to have the funds and property of the BAS transferred to it. The Astronomical Society of Queensland therefore regarded itself as the direct successor of the earlier Society. However, new information available through Trove tells a different story. As advertised in *The Brisbane Courier* on 17 March 1917, the telescope was to be sold by auctioneer A. S. Phillips on 21 March 1917 (Anon., 1917a).

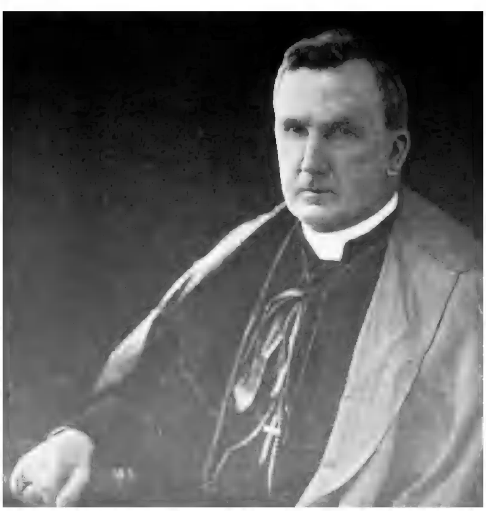
Sale of the Grubb Six-inch Refractor, a New Observatory, and the Demise of the Brisbane Astronomical Society

The following news item appeared in *The Brisbane Courier* on 26 March 1917:

> **The Ardencraig Telescope.**
> The fine 6in. astronomical telescope from Ardencraig, Toowong … was disposed of at auction at Mr. A. S. Phillip's mart on Saturday morning, when it was purchased on behalf of Dr. Duhig, Roman Catholic Archbishop of Brisbane, for £85. Dr. Duhig states that the telescope will be mounted at one of the Roman Catholic colleges in the Brisbane district, where arrangements will be made for scientists, students, and the public to have access to it (Anon., 1917c.).

Note that James (later Sir James) Duhig (1871–1965) (Figure 10) had been appointed Archbishop that year (1917), the beginning of a long and illustrious career that would see Catholic churches crowning many hilltops in the Brisbane area.

Figure 10. Archbishop James Duhig (after Nudgee College 'Annual', 1924).



With this sale, the successors of the Brisbane Astronomical Society could lay no claim to the telescope, and soon after, the following public notice appeared in *The Telegraph* (Anon., 1917d):

> THE BRISBANE ASTRONOMICAL SOCIETY.
> The Committee have decided to distribute the proceeds amongst the original subscribers in proportion to their subscriptions.
> No claim recognised which is not made before 1st August, 1917.
> Address : ROBERT H. MILLS,
> A.M.P. Chambers, Brisbane.

For 12 months after Archbishop Duhig purchased the telescope, it was in the workshop of Mr H. W. Valle (a well-respected Brisbane instrument maker who also sold and repaired surveying equipment), undergoing restoration (see Figure 11). He charged £45 for removal, restoration and storage, and £400 fire insurance (Catholic Church archives) – this surprisingly large latter figure possibly the estimated replacement cost.

Archbishop Duhig planned to install the telescope at St. Joseph's College on Gregory Terrace in 1918 in conjunction with a new Science Hall, but it was removed from Valle's workshop before the Science Hall was completed, and instead went to a new observatory at St. Leo's College on Wickham Terrace in 1919 (Head, 1991). Figure 12 shows that the building was rectangular and aligned N–S, E–W, and contained a dome and adjoining transit slits within the same roof line and building footprint. A 1924 Brisbane City Council plan shows a second 8-feet square room on the eastern side.

In detailing the history of St. Leo's College, Father Michael Head (1991) describes how construction of the observatory in 1919 was "… under the direction of Mr J. Beebe, a man greatly interested in astronomy, who gave a number of night lectures on the subject to college students". As an architect and former owner and builder of the East Bendigo Observatory in Victoria, John Beebe (Anderson, 2020; Martin & Orchiston, 1987) was an excellent choice to design the observatory and oversee the project. Researchers should note that Father Head incorrectly identified the Grubb telescope as coming from the estate of Clement Wragge (1852–1922); however, at this time the former Queensland Government Meteorologist was alive and well and living in Auckland, New Zealand.

In *The Ascent of Tabor: Writing the Life of Archbishop Duhig*, Father T. P. Boland (1986)

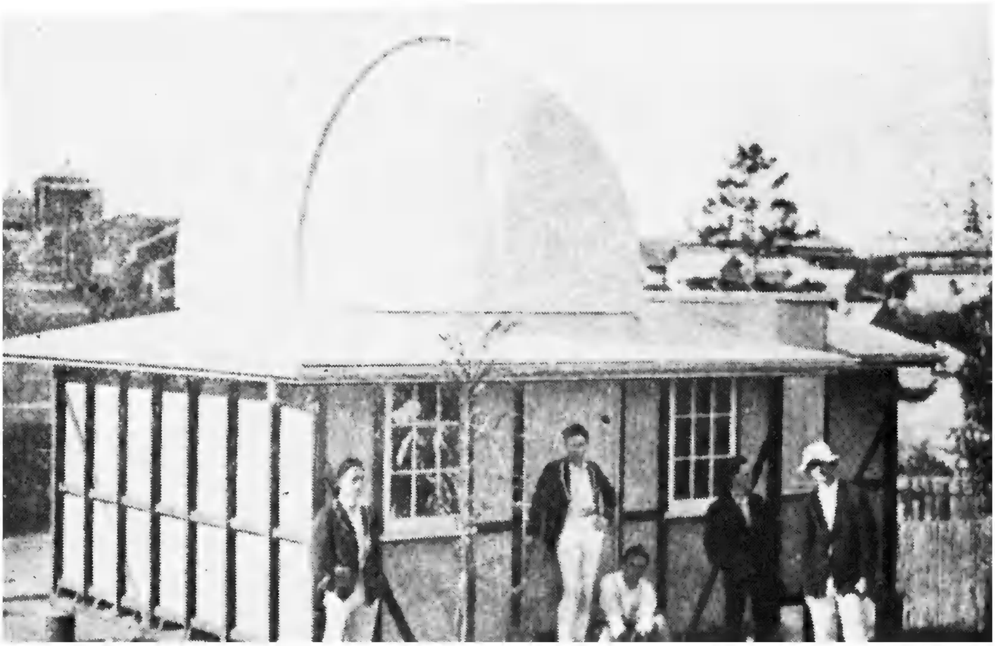
claims that the Archbishop saw himself as a patron of the sciences, and apart from St. Leo's College Observatory there were other examples involving plans for telescopes, observatories and the acquisition of scientific equipment, and their donation to church institutions.

Towards the end of the 1920s, the telescope fell into disuse and the "lenses" (presumably the eyepieces rather than the 6-inch objective) were stolen (Head, 1991). A 1946 aerial photo shows the observatory building still there, but around this time the land was added to the new Holy Spirit Hospital next door. A 1951 aerial photo shows the building gone, and in 1960 St. Leo's College moved to The University of Queensland campus at St. Lucia.

There is no published record of what happened to the 6-inch Grubb telescope after this. However, Bill Kitson (pers. comm., 2020) notes that on 24 April 1952 the well-known Brisbane long-range weather forecaster Inigo Jones gave a lecture to the Historical Society of Queensland titled "My Seventy Seven Years in Queensland". He described visiting Mr Stanley many years earlier, and he then referred to "... the Grubb telescope now at Nudgee College and which I was one of the first people to see through. Later His Grace Archbishop Duhig offered me the use of this instrument." We must presume Jones declined Duhig's offer and that the telescope was then transferred to Nudgee College. However, an extensive search by the college archivist failed to uncover any evidence of the telescope. It may have been placed in storage and not properly recorded (Kitson, pers. comm., 2020). Nearly 90 years have elapsed since the telescope was allegedly given to Nudgee College, so it is possibly still there, stored, neglected and long forgotten.

Figure 11. A view of part of Valle's workshop in 1917, showing the 6-inch Grubb refractor on the left (after Kitson & McKay, 2006).

Figure 12. The St. Leo's College Observatory in 1919 (after Head, 1991).

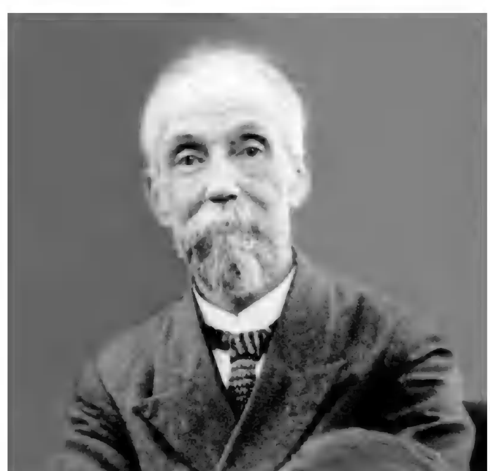


Meanwhile, research by Bill Kitson (pers. comm., 2020) has revealed that the St Leo's College Observatory transit instrument was made by William Wray (1829–1885), a well-known English telescope maker. After the observatory ceased to function, this instrument was at The University of Queensland for a period while surveying courses were conducted, and was then sent to the Queensland Museum of Lands, Mapping and Surveying.

The Queensland Popular Science and Art Society and the Twelve-inch Reflecting Telescope

Reports published in *The Telegraph* (Anon., 1919a) and the *Daily Standard Brisbane* (Anon., 1919b) state that on Saturday, 10 May 1919, Dudley Eglinton (Figure 13) held a meeting at his residence in Toowong, and the Queensland Popular Science and Art Society was formed. There were about 35 people present, including several dignitaries. Mr Herbert F. Hardacre (1861–1938), the Minister for Education and Secretary for Public Instruction, was the chairman. Those at the meeting were informed that while astronomy would be the central pivot of the new Society, it would embrace all branches of science and art.

Figure 13. Dudley Eglinton in 1918, not long before he formed the Queensland Popular Science and Art Society (Photo courtesy of Richard Tassicker).



Those at the meeting also learned that "... Mr Eglinton had succeeded in purchasing an excellent telescope ..." (Anon., 1919c) with funds subscribed, and it would be the property of the Society (Anon., 1919d). Using Society subscriptions to purchase a telescope was reminiscent of the acquisition of the 6-inch Grubb refractor by the BAS back in 1896. This time it was a 12-inch reflector. Mr Hardacre promised to provide the Society with access to a large meeting room in the old Fire Brigade Building (Figure 14) that was under his jurisdiction (Anon., 1919c; Anon., 1919d).

Figure 14. The Old Fire Brigade Building, Ann Street, in 1891 (Source: State Library of Queensland).

Neither J. P. Thomson nor John Beebe was mentioned as present at the meeting of the new Society, which was not surprising given the clashes between Thomson and Eglinton over the 6-inch Grubb telescope and Beebe's involvement with the St. Leo's College Observatory.

The 12-inch reflecting telescope Eglinton purchased in Sydney for the new Society appears to have belonged to George Hoskins (1883–1953) (Orchiston & Bembrick, 1997), a prominent British Astronomical Association (New South Wales Branch) member, who in 1917 had replaced it with an 18-inch reflector (Orchiston & Bembrick, 1995). After he acquired the 18-inch reflector, there was no further mention of the 12-inch telescope in Sydney, and we know from later events (ibid.) that Hoskins was in touch with Brisbane astronomers at this time, so the sale to the Brisbane Society is logical.

On 24 June 1919 *The Brisbane Courier* reported that:

> ... the large telescope purchased in Sydney would be forwarded by rail at once, and could be expected in Brisbane during the coming week. It is proposed to exhibit it in the windows of Messrs. Smellie and Co.'s shop in Queen Street for a few days. Arrangements will then be made for placing it on top of the Old Fire Brigade Station, near the Central Railway Station. Although this is not regarded as an ideal position, it will afford many advantages, at least temporarily, and will be very accessible (Anon., 1919c).

On 3 July 1919, *The Telegraph* reported on a meeting of the Council of this Society, and that: "As soon as the telescope is placed in position and safely housed, astronomical observations will begin, and public lectures on astronomy delivered by Mr Dudley Eglinton, F.R.A.S., under auspices of the society ..." (Anon., 1919d). On 28 July 1919, *The Telegraph* reported the display of the telescope; that it had been made by Calver (indicating its quality); that the mirror was being re-silvered; and that: "A platform and small house to protect the telescope are to be erected" (Anon., 1919e). The "small house" was Stanley's observatory that was relocated to the roof of the Old Fire Brigade Station (Steve Hutcheon, pers. comm., 2019).

But progress was slow in making the telescope operational (Anon., 1919f), and on 28 February 1920 Eglinton mentioned that "... its complete adjustment has not yet been effected, and some month or two must elapse before the telescope can become usable" (Anon., 1920).

Eventually the telescope was operational, and certainly by 21 September 1922 when *The Brisbane Courier* reported:

> THE TELESCOPE AT THE OLD FIRE BRIGADE STATION.
> Mr Dudley Eglinton, F.R.A.S., advised the "Courier" last evening that he would be at the telescope housed on top of the Teachers' Training College (old Fire Brigade Station), at the corner of Edward and Ann streets, this afternoon, between 3 and 5 o'clock, and would be pleased to see all who had subscribed towards the purchase of the instrument (Anon., 1922).

The time and date were not randomly selected, because that very afternoon a total solar eclipse swept across Australia. Brisbane was slightly north of the track of totality, but nevertheless 98.3% of the Sun's disc was covered at maximum at 4.15 p.m., leaving only a very thin visible crescent. Thus, Dudley Eglinton was once again using a telescope for a public demonstration.

After this date, there were few references in Brisbane newspapers to the Queensland Popular Science and Art Society or the 12-inch telescope, though Eglinton continued to lecture and write articles.

Dudley Eglinton became totally blind in 1924 or 1925, ending his involvement in public viewing nights. He had single-handedly occupied the position of 'demonstrator' for over a quarter of a century, first with the 6-inch Grubb refractor and then with the 12-inch reflector. It is believed no one could be found to fill his shoes.

The 12-inch telescope remained atop the Old Fire Brigade Building/Station for a number of years, largely unused. It was moved several times and refurbished, eventually coming to the Astronomical Society of Queensland, but it lacked a satisfactory permanent home. The Sir Thomas Brisbane Planetarium now has the primary mirror, other optics and some fittings, and these are on display occasionally. The main mirror is historic. Its rear is engraved as follows: "With of Hereford made me in February 1877" and "Corrected by G. Calver /04" (see Figure 15). Both George With (1827–1904) and George Calver (1834–1927) were well-known and respected English telescope makers (Marriott, 1996; Dall, 1975).

Figure 15. A close-up of the rear of the 12-inch mirror showing the inscriptions (Source: Mark Rigby).

Concluding Remarks

The period from 1890 to 1920 saw a flowering of interest in astronomy throughout Australia (see Haynes et al., 1996), but unfortunately the population base and demographics of Brisbane at this time were not sufficient to maintain a local astronomical society. Thomson made this point in 1897. Unlike in Sydney, Melbourne and Adelaide, there were no role models with international reputations who were committed to observational astronomy, and there was no government-funded professional observatory to foster amateur–professional relations and encourage serious observing programs (Orchiston, 2017). The BAS also was formed for the wrong reason – to keep a 6-inch refracting telescope in Brisbane, rather than to foster observational astronomy and telescope making, as occurred in other contemporary Australian astronomical societies (Orchiston, 1998). Consequently, the BAS went into a steep decline soon after its formation in 1896 and achieved very little. Even its centrepiece, the 6-inch Grubb refracting telescope, although later installed in a new observatory at St Leo's College, was only in operation there for a fairly short period before being lost forever.

The two main BAS protagonists, Eglinton and Thomson, memorably clashed in 1897 soon after the formation of the BAS, and again two decades later in late 1916, in both cases regarding the Grubb telescope.

Individuals like Thomson, whose main interest was not astronomy, were able to achieve much in their chosen fields. Thomson's own position with the organisation he founded in 1885, the (Royal) Geographical Society of Australasia, Queensland, was very similar to Eglinton's with the BAS, but in contrast, Thomson was successful. He actively promoted and supported the Society throughout his life, and it is still extant. Over the years, he received due recognition for his promotional work and his research, including an Honorary Doctorate and a CBE.

Eglinton doggedly and unsuccessfully supported the Brisbane Astronomical Society and later the Queensland Popular Science and Art Society. He employed the same formula he had used for the 6-inch refractor, to fund a 12-inch reflecting telescope for the latter Society. This telescope, when finally operational in 1922, was only in use for a very short period before Eglinton became blind, which put an abrupt end to his observational endeavours. There were then no further signs of life from the new Society. The overall impression is one of sadness at Eglinton's failure to maintain a viable astronomical society and produce useful scientific results, but he was not a research astronomer. He had the personal satisfaction of being appointed a Vice-President of the newly formed Astronomical Society of Queensland in 1927, and in 1935 being made an Honorary Life Member.

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Research by Steve Hutcheon into the history of various late nineteenth and early twentieth century telescopes in Queensland prompted the first author's interest in the subject. Steve's continued dogged research provided much of the background for this paper. Mr. William (Bill) Kitson, Retired Senior Curator, Museum of Lands, Mapping and Surveying (Queensland Government), has been exceptionally helpful in providing information in his own sphere of expertise and has made a very valuable contribution to this paper. We also express our appreciation to staff at the State Library of Queensland for their assistance, and we are grateful to Richard Tassicker and Katie Eglinton (descendants of Dudley Eglinton), Marilyn England (Toowong History Group), Mark Rigby (Curator of the Sir Thomas Brisbane Planetarium), Museums Victoria, the Queensland Museum of Lands, Mapping and Surveying, and the State Library of Queensland for kindly providing images used in this paper. Finally, special thanks go to the Honorary Editor PRSQ, Angela Arthington, for her guidance and assistance.

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Author Profiles

Peter Anderson has been President of the Astronomical Association of Queensland and its predecessors on five occasions since 1966. In addition to active participation in astronomical tourism, especially to observe total solar eclipses, Peter has been a guest lecturer on cruise ships for nine years presenting astronomical topics. He has also written many articles and is an active contributor in the field. For the last 40 years he has conducted astronomical research from his observatory at The Gap, Brisbane, specialising in the field of lunar and asteroidal occultation of stars. Peter maintains a strong interest in the history of Queensland astronomy.

Professor Wayne Orchiston is affiliated with the National Astronomical Research Institute of Thailand and the Centre for Astrophysics at the University of Southern Queensland. A former amateur astronomer and President of the BAA (NSW Branch) and the Astronomical Society of Victoria, he has published extensively on Australian astronomy, including a book about John Tebbutt. He has also published on aspects of Chinese, English, French, German, Indian, Indonesian, Japanese, New Zealand, Philippines, South Korean, Thai and US astronomical history. Currently he is President of IAU Commission C3 (History of Astronomy), and Minor Planet '48471 Orchiston' has been named after him.

Royal Society of Queensland Reports

Science Through a Big Window

Presidential Address 2020

Ross A. Hynes

It has been a strange and difficult year of ongoing drought, fire, flood, pandemic and economic disruption – a year where the tools of the digital age have become more essential for the continuity of scientific research, communication and education. What can we learn from our 2020 experience? *Business as usual will not solve our present and emerging human and biosphere-related problems!*

Life System Interconnectedness

One underlying reality has become increasingly clear, i.e. the interconnectedness of life systems. Never in recent times have ecological relationships for our species and associated biodiversity within ecosystems at a global scale been so powerfully exposed under the impact of climate change. This existential emergency is expressed as increasing intensities of fire, flood and accelerating ecosystem degradation with increasing pollution, in parallel with the ongoing realities of zoonosis, in the pandemic COVID-19.

The condition of the world's ecosystems has moved a long way from Sir Arthur Tansley's (1935) perceptions of the then conservation status of vegetation systems within his experience (Tansley (Ed.), 1911). Notwithstanding this, his initial broad definition of ecosystem is still relevant and applicable today. Paraphrased, the term 'ecosystem' was coined to recognise the integration of the biotic community and its physical environment as a fundamental unit of ecology – within a hierarchy of physical systems from atom to the universe.

So much change has occurred over most of the biosphere since 1935 that we are now dealing with what some researchers call 'novel ecosystems' (Hobbs et al., 2006). Irrevocable decisions by government and landholders have created 'novel ecosystems' that have changed the nature of land management problems and our economic and environmental capacity to contribute to theory-based models to underpin sustainable on-ground practices (UN Report, 2018). The original values have been modified, destroyed or coalesced with invasive species, complicated by waves of land degradation, which are ever increasingly influenced by the vagaries and intensifications of climate change (Hobbs et al., 2006). It also needs to be recognised that prior to 1788, it is unlikely that any ecosystems in Australia were not influenced in some way by Indigenous cultures (particularly by fire) over the previous 60,000 years or so. During the last 240 years, our complex society has not in general been modifying a pristine wilderness, although the landscape certainly contained and continues to have locations of high wilderness value.

In recent times, at least four approaches to ecosystem science can be identified:

1. *Biologically centred*. This approach considers the 'organism' as the focus of study within an ecosystem.
2. *Process-oriented*. This approach views the ecosystem as a set of processes, focusing mainly on the flow of energy and matter.
3. *Geographical*. A geographic space that recognises the ecosystem unit as an area of sufficiently similar topography, climate and biology (Blew, 1996).
4. *Heuristic*. An ecosystem is really no more than a conceptual device (MacFadyen, 1975).

Conceptually, there may also be hybrid versions of the above. In this address I use the basic concept of Tansley (1935) that, as a starting point, "an ecosystem, is the complex of living organisms, their physical environment, and all their

interrelationships in a particular unit of space" (Encyclopaedia Britannica, 2020).

It is little wonder that developing a relevant theory of ecosystem science has remained problematic. There are serious limitations regarding the present underlying theoretical base. The challenge of rigorously understanding information flow and linkage between different levels of scale remains a persistent problem. There is no unified theory of ecology. *We cannot predict the production of wheat in a wheat field by measuring the electron transfer on the surface of a granum in a chloroplast of a wheat leaf!* This is my usual example, when seeking to explain that the 'scale distance' between levels can often place many predictions in an absurd position. Rather than becoming the mainstream challenge for ecology, ecological research has for many decades focused on those who seek to expand knowledge by deep understanding at the micro (biochemical/physiological) end of the spectrum and those who seek to place investigations in a geographic-landscape context.

Notwithstanding this, we can seek to identify emergent properties that can assist in linkage between levels of scale. Further, we now have tools that can significantly assist those researchers involved, e.g. supercomputers, parallel processing, integrative analysis protocols and next-generation algorithms – in conjunction with multiple inputs from big data (including remotely sensed), more powerful error rectification and reconciliation methods between datasets, and rigorously described and validated metadata that define the limits of dataset use, et cetera.

We need to use these tools. Nevertheless, and understandably, most scientists appear more comfortable when working at more manageable scales and largely employing traditional hypothesis-testing approaches. Their papers can be more readily published. That is how, at present, they mainly get recognition and satisfy their terms of employment.

A 'business as usual' approach in scientific research will not solve our current 'big' problems, e.g. global warming, sustainable energy to drive human societies, COVID-19 and the inevitable onset of further zoonotic impacts. However, in the current era, solutions to whole-system problems usually remain unsolved – until we, as a super-generalist species, face a crisis. History tells us that our ability as a species to foresee a crisis and take timely evasive action is also very limited. Perhaps the best example of that is the fact that at least 40 years have passed since prescient scientists began to warn of impending anthropogenic-affected climate change and other serious problems related to pollution and loss of biodiversity. In the future, with the coalescence of global drivers in relation to environmental, social, cultural and economic conservatism, we are likely to rapidly reach thresholds – ecological tipping points when crisis responses will not meet the challenge. As the Global 2000 Report makes clear (Speth, 1980), previously we needed to act much earlier, but regarding the big problems it has become crucial that we act seriously, intelligently and urgently – now! That was forty years ago!

Developing a Personal Wide-window Approach to Ecological Science

To explore some of the challenges involved, I will briefly refer to a few of the investigations I have previously conducted or led and some of their outcomes. These projects address steps towards wide-window understandings as elements in a whole-systems approach to ecological science.

First, let us revisit some basic principles of systems science:

- A system can be any scale. This could range from a leaf if we are investigating, say, fungal impacts on specific plants, to the Earth if we are considering global climate change. Thus, the level of focus needs to be clearly defined.
- In hierarchy theory relevant to systems research, three levels of importance are usually recognised: the level of observation; the level below – which influences or explains what happens at the level of observation; and the level above – which is influenced by the changes that occur at the level of observation (Hynes & Scanlan, 1993).

Systems scientists look for general principles that can apply across both natural and social sciences. They support the position that reductionist methods cannot produce a comprehensive understanding of 'organised' complex systems (Barlow, 1992). Methods include multidisciplinary and cross-scale research strategies.

Let me place in context my approach to wide-window ecological science and how it has evolved over the past 50 years. An address is not intended to be a book, so I have selectively and briefly followed the development and application of four conceptual frameworks. These comprise: *multi-level ecological analysis*; *preliminary conservation zoning for areas of high biodiversity*; and as complementary conceptual and analytical strategies, a brief acknowledgement of *conservation potential in forests and woodlands* and *the regeneration niche and the establishment niche of plants*.

Multi-level Ecological Analysis (M-LEA)

This includes ecological analyses that have employed frameworks that included GISs (geographic information systems) and IMSs (information management systems), numerical classification and ordination of data inputs – refined and distilled by sets of scientific filters.

The rationale of my study of the ecology of the *Nothofagus* forests in Central New Guinea (Hynes, 1973; Hynes, 1974a) created debate among supervisors and examiners as to whether I should even be allowed to proceed with this approach.[1] This incorporated 10 representative sites across the Central Highlands of New Guinea (ranging from 945 m–2682 m above mean sea level), focusing down to two major sites with nested studies investigating their environments and biotic communities and population cohorts of Antarctic beech (*Nothofagus* spp.) and associated species extant in these ecosystems. The Webb (1970) Rainforest Pro Forma was used when surveying structural and physiognomic characteristics on all sites (Hynes, 1974b). The studies also included soil and plant litter analyses and relevant plant physiological investigations. Detailed floristic and forest structural investigations (trees and saplings) were conducted on random stratified grids in two intensive sample plots on each of the major sites on Mt Giluwe and Mt Michael. Seedling studies and gap analyses were also conducted. This was the first detailed ecological study of these forests in Papua New Guinea (Johns et al., 2007).

Notably, the International Biological Program (IBP 1964–1974) introduced as one of the then main 'new technologies' a *systems-based approach* to global biological and related environmental investigations (Specht & Specht, 2020). The approach taken for my New Guinea Nothofagus Forests study was a preliminary application of this 'new technology'.

A more comprehensive framework was implemented in my work on the ecology and conservation potential of remnant woodlands in the Northern Pennines of England (Hynes, 1978a)[2]. This work comprised a multi-level ecological analysis of mixed deciduous woodlands. Investigations ranged from woodland surveys to analyses of tree increment (girth at 4.5 m) in the sampled woodlands and seedling growth on five sites over an altitudinal range of 229 m (750 ft) to 823 m (2700 ft). Detailed soil investigations (5 woodlands) were conducted, and climate data was continuously monitored at 305 m (1000 ft) on the major study site (Seedling Site 2). These investigations were complemented by tree seedling growth-cabinet investigations that simulated summer growing temperatures over the altitudinal range, which provided further insight. Multi-variate techniques, viz. numerical classification and ordination and traditional statistical methods were used to examine the database. Trees and seedlings of dominant species ash (*Fraxinus excelsior*), birch (*Betula pubescens*), sycamore (*Acer psuedoplatanus*) and rowan (*Sorbus aucuparia*) were used as biological indicators of ecosystem functioning throughout. Investigations of increasing intensity were conducted over the following levels:

- Zone II (elevated remnants) – 155 woodlands.
- Upper level survey – 18 woodlands.

[1] Page 89 summarises my approach at that time: "Ecological studies directed towards the biological community level by their very nature become holistic. The obvious criticism of this approach is that it attempts too much. This will always be partly true no matter how judicious a selection of areas for investigation is made. The justification submitted here for largely adopting this method in this work is itself ecological. For it is considered that only by seeking to come to grips with the problem by viewing it selectively in part and then as a whole, while acknowledging dangers inherent in such method, that a truly ecological perspective can be gained."

[2] Commonwealth Universities Scholar, University College London and the Department where Arthur Tansley first studied and taught.

- Tree vegetation (community structure/habitat studies) – 5 woodlands.
- Dendrometer investigations – 3 woodlands.
- Seedling studies – 3 in woodland and 2 above the tree line.
- Ecological synthesis investigations and a comprehensive statistical model – 1 woodland (major study site).

Multi-level analysis is an effective focusing, sorting and sieving mechanism for ecological studies that move though different levels of investigation, seeking meaningful linkages and understanding. A conceptual framework of M-LEA is presented in Figure 1.

When applied to investigate the need for a 'wide-window' framework to test research project relevance and likely effectiveness of outcomes in seven cases of weed research, three cases highlighted the need for wider research frameworks; the other four cases highlighted the need to identify key relationships between land use problems and comprehensive solutions. Both commentaries sit logically within the business of whole-systems science.

Figure 1. A simplified but graphical representation of the analytical processes employed in multi-level ecological analysis and the sequential stages though which it progresses. A detailed expansion of these stages is presented in Hynes (1978a), which also examines the theoretical challenges of connectedness between levels of scale and information links and flow. Logistically, the stages can be carried out in parallel during project implementation and integrated where and when research outcomes become available.

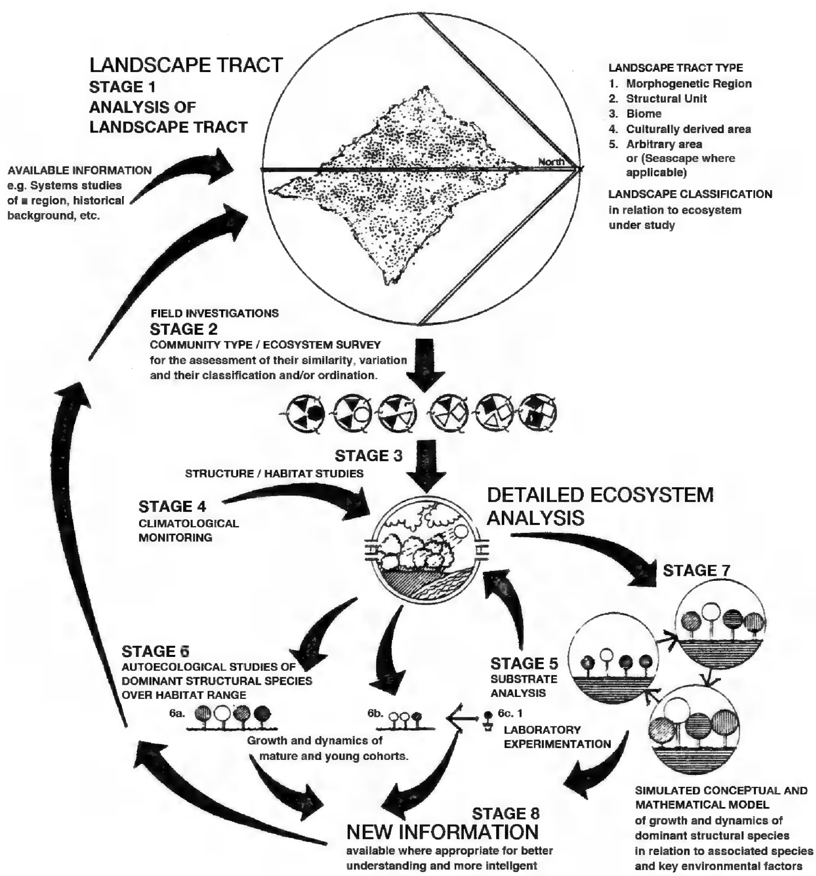
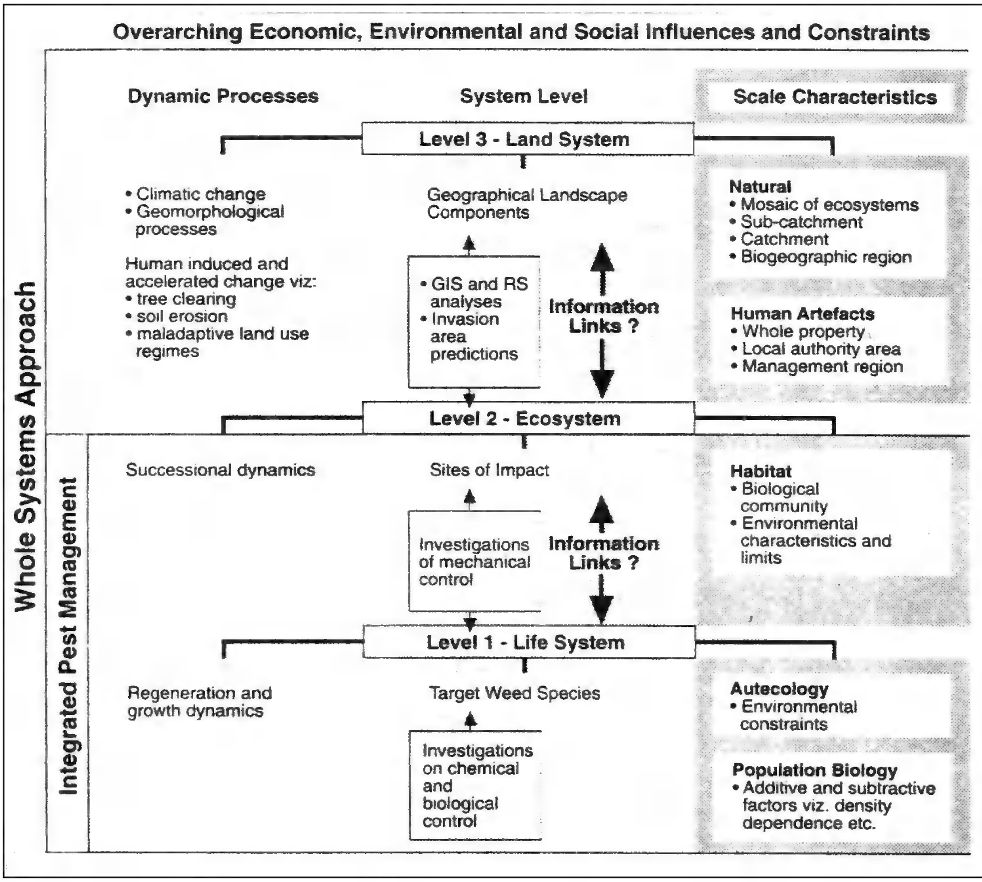


Figure 2. An operational framework for accommodating levels of organisational and physical scale in pest plant research. Systems modelling using computer protocols can be conducted at any level and used for linking information outcomes between levels. The framework can be used to test specific research investigations regarding whether or not they satisfy the implications of viewing the work through the wider framework provided by M-LEA or whether or not they need to identify key relationships between land use problems and comprehensive solutions (Hynes & Scanlan, 1993).



Preliminary Conservation Zoning in the Wet Tropics of Queensland

(a case study in conservation zoning for areas of high biodiversity)

The Wet Tropics of North Queensland is a region of high environmental and socio-economic complexity. In response to the challenge of land planning and management in the region, the Queensland Government established the Northern Rainforest Management Agency (NORMA) in 1987. I was appointed project leader and chair of the Scientific Advisory Committee.

A report on the work of NORMA (Hynes (Ed.), 1988) focused on scientific and technical matters related to the development of land resource zones. These zones were defined to be consistent with the essential themes of the World Conservation Strategy, the Australian National Conservation Strategy and the World Commission on Environment and Development report (1987), 'Our Common Future'.

The report had two major objectives:

1. To use data outputs from three parallel resource analyses in conjunction with the application of explicit scientific and management filters to produce an objective, strategic conservation zoning.
2. To draw conclusions and make recommendations pertaining to future sustainable multiple use of the resources in the region that were compatible with its nature conservation values; see Figure 3 (Hynes (Ed.), 1988; Goosem et al., 1989).

A graphic overview of the relationship between data sources and their analyses is presented in Figure 3.

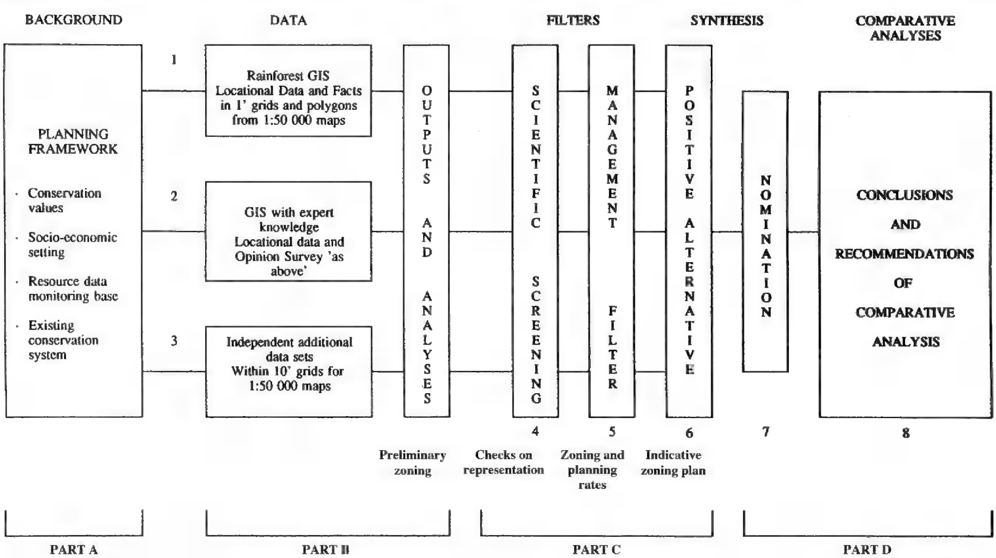
The report developed and applied concepts and approaches useful in identifying alternatives for decision makers in conservation planning. Several innovative methods were employed. One of the outcomes was an indicative dominant land-use suitability zoning map (Figure 4). This zoning approach best complied with the criteria for a Biosphere Reserve as described by the IUCN (1980). This work was a step on the way to a more comprehensive plan for the Wet Tropics.

This planning process under NORMA was superseded by the declaration of the Wet Tropics World Heritage Area (WHA) in 1989. Notwithstanding this, the GIS principles and issues involved are the same as those being adopted for the present WHA (Goosem et al., 1989). This work highlights the effectiveness of an analytical framework in managing multi-sourced data inputs and how the Queensland Wet Tropics GIS can produce, from its >350,000 species locations and other key information layers, valuable zoning outputs.

Complementary Frameworks Developed Over This Period

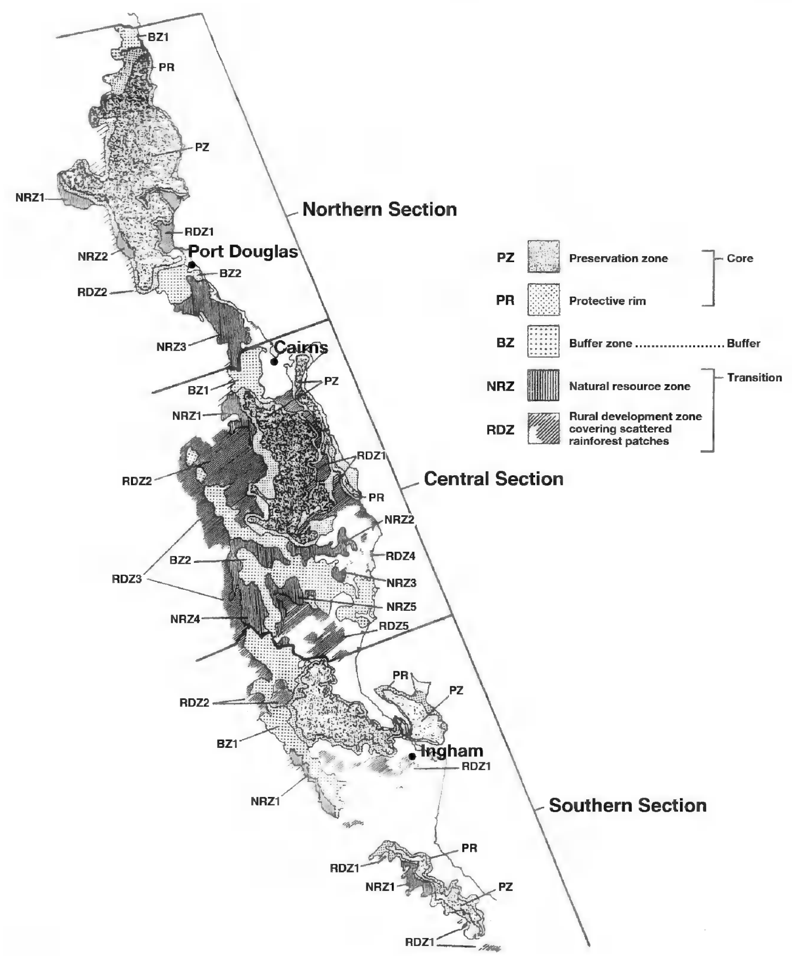
- *Comprehensive framework models of the establishment of tree seedlings, which encompass the regeneration niche and the establishment niche.* These frameworks were developed following the work of Harper (1977) and Grubb (1977) and have been applied and published in Hynes & Chase (1982), Hynes (1983), Hynes (1984) and Hynes (1989).

Figure 3. A flow diagram of the relationships between data sources and their analyses and the screening and integrating process involved in the NORMA project (Hynes (Ed.), 1988). This is an example of M-LEA applied to analysing large independent data sources as inputs to scientific screening and management filters in identifying options for conservation zoning in the Wet Tropics of North Queensland.



- *Conservation potential as a tool in vegetation restoration*. Conservation potential assesses the capacity of the landscape to return to its original condition through natural successional processes. This framework was developed in my woodland ecology project and continues to evolve over the years (Hynes, 1978a; Hynes, 1998; Hynes, in Davie & Ridwansyah, 2016).

Figure 4. Dominant land use suitability scenario-indicative zoning map of the Wet Tropics of Queensland. This presents an optimised preservation strategy with complementary conservation zones for multiple resource use. This synthesised output of the M-LEA approach, which provided an alternative land use and conservation scenario for the region (Hynes (Ed.), 1988) was superseded by the declaration of the WHA but provided an input to its initial planning. This indicative scenario is the computerised output of Stage 6 of the process outlined in Figure 3.



Zoning schematically presents the regional and sub-regional relationships between the zoning classes and resource use options. These classes define the dominant land uses in a zone. Other land uses can be present, but the controls and resource use prescriptions defined would be directly related to the nature of zoning class. Definition of land tenure types and refinement of cadastral boundaries make up the next stage in this process. Buffer zones, natural resource zones and rural development zones are numbered generally in a north–south order within sections.

These frameworks can complement M-LEA when applied as a part of the toolkit in investigating relevant components of whole-systems studies but are not explored further in this address.

Big Data and Whole-systems Science

In the foregoing cases the methods used were mainly employed prior to the evolution we are now experiencing in contemporary methodology for big data science. Notwithstanding this, they show how an individual's applied ecological research experience can strengthen awareness and help validate the application of multi-level and multidisciplinary frameworks in seeking understanding of the environmental problems that challenge us.

Ecology has recently seen rapid growth, driven mainly by advances in technology, greater access to big data and a growing awareness of the interconnections between humans and natural systems. As a discipline it has expanded beyond traditional themes and reductionist investigations to cover anthropogenic and contemporary data-rich, micro- and macro-scale themes. Increased availability of complex data, coupled with advances in technology and analytical capacities, has enabled this expansion from a classical theoretical discipline to a data-driven, multidisciplinary science that can apply knowledge to whole systems and their problems. Ecological research themes have shifted significantly over the past four decades (McCallan et al., 2019). (Notwithstanding this, we are still in dire need of a rigorous ecosystems-science theoretical base.)

The five key components of effective data management contributing to this expansion include measurable improvements in data quality, data access, data integration, data network and systems interoperability, and governance (Hynes, 2005). Hynes also elaborates on IT and information management tools, e.g. networks, distribution hubs, and, where relevant and essential, high-performance scientific computing. Information management systems (IMSs) need to be based on rigorously developed data models, and data inputs need to recognise data lifecycle constraints and the need to fill gaps with strategic data capture. The flow of data and information and data sharing between users, data generators and data custodians will be largely reliant on the quality of the interoperability of the IMSs involved (Hynes & Jones, 2004).

Paths to data access include: trawling and weaving; whole-systems approaches; and web-based access. Whereas the last two are usually essential for a whole-systems approach, they demand detailed descriptions. I will briefly comment on the first path here. A supportive path a user can follow when retrieving data is to apply a data-drilling, -trawling and -weaving approach. This can develop information summaries of similar information across many resources (databases). Here the concept of a 'data piece' is one way that information can be arranged that enables more efficient data integration (Gordon et al., 2003).

Big natural resource data analyses are not new to Australia or Queensland. Nevertheless, we have had a tendency to lose continuity and purpose because political decisions have often closed down statutory bodies responsible for crucial data management (Marlow, 2020). These bodies include: The Resource Assessment Commission (RAC, 1989–1993); the National Land and Water Resources Audit (NLWRA, 1997–2008); and the Queensland Regional Open Space System (ROSS, 1994–2012) (Marlow, 2020).

As a consequence, there remains a need for rigorous integration and perceptive, critical analyses of environmental big data at national and state levels. This deficiency currently limits the decisions we need to make in plotting the best pathways for sustainable management. It is more important than ever that we urgently rectify this situation to strengthen our chances of successful medium- and longer-term environmental and social outcomes.

Here I briefly overview some data-capture, data-management and integration approaches that allow effective input to big data investigations. These include: NEON (the National Ecological Observatory Network) in the USA; QLDGLOBE (Globe Queensland); and a precursor expert subsystem, ENRII (Environment for Natural Resource Information Integration); and One Health (OH) for *Homo sapiens* and Other Species, another established big data and coordination system of note.

NEON

The National Ecological Observatory Network became fully operational across 81 locations

(47 terrestrial and 34 aquatic), from Alaska to Puerto Rico, in May 2019. This marks a significant step forward in the history of ecology and will provide a substantial investment ($US2.4 billion) in continental-scale ecology. Its construction and maintenance will extend over 30 years (Balch et al., 2020). It is predicted that NEON will precipitate the next big shift in the discipline. Already, early adopters have produced over 80 broad-scale publications using NEON assets and 22,000 data downloads in the past two years.

Two major challenges have emerged. The first is to *build the core skills* necessary for open data-intensive ecology. An open data approach from the outset is a transformational element; however, essential skills are needed, and these include:

- best practices for developing and sharing – data, code, software, and entire scientific flows;
- comprehensive analyses of vast quantities of data on distributed cyberinfrastructure or the cloud; and
- collaboration skills in an open science framework that facilitate large-team science (Balch et al., 2020).

The second is to link NEON to major existing environmental datasets. There are at least four major additional environmental data sources that need to be harmonised with NEON. These include:

- existing observatory networks;
- emergent observing sensors and platforms, e.g. satellite systems such as Landsat and its derivatives;
- climate and land-use data; and
- derived simulation models.

Alone, NEON is powerful; combined with other data sources, it will be transformational.

Unique to NEON within ecology is its highly centralised infrastructure, management and data services. Despite its widespread footprint, all design and priorities flow from its headquarters (HQ) in Boulder, Colorado, and all data flow back for processing and posting to the HQ portal. Once posted, all data is freely available for download by anyone (SanClements & Thibault, 2019).

The vision is that the growing NEON science community will become the cornerstone of North American eco-science for the next three decades and address the continental-scale ecology questions it was designed to answer (Balch et al., 2020).

QLDGLOBE (Globe Queensland)

The Queensland Government and community stakeholders have had a dedicated interest in spatially defined natural resource data and its management for many decades (Hynes & Johnson (Eds.), 1989). Previously, this was held with associated datasets in data silos across a number of departments, usually specifically linked to their core business.

Globe Queensland was established in 2013–2014 (Jacoby, 2013, 2014). Built on Google Earth (GE), it provided an open portal to Queensland Government spatial and associated data in the GE format. It was replaced by a dedicated Globe Queensland system in 2017, along with several more specific data platforms such as QTopo, QImagery and MyMinesOnline. These platforms provide user-friendly, read-only services of hundreds of spatial datasets such as roads, property and land parcels, topography, mining and exploration, land valuation and natural resources (vegetation, water, soil, etc.). Other pathways for accessing many of the same datasets for independent spatial analyses, can be downloaded under prescribed copyright restrictions and various licensing arrangements via:

1. QSpatial (2020): http://qldspatial.information.qld.gov.au/catalogue/custom/index.page
2. Open Data Portal (2013): https://www.data.qld.gov.au/dataset

Whilst these datasets have became openly accessible to the community, each of the contributing government departments has retained their role as custodians of their datasets and the metadata describing them (Jacoby, 2013, 2014).

With changes of government came structural adjustments in agencies. Natural Resource Sciences, Indooroopilly were custodians of NR datasets during the 1990s and into the 2000s, and when the Dutton Park Ecosciences Precinct was completed and established in 2011, it became the repository for these datasets.

As manager of Natural Resource Information Management at the Natural Resource Sciences, Indooroopilly facility from 2000 to mid-2005, I was able to support a number of projects that

contributed to the NR data silo. These projects, amongst others, included the development of the Soil And Land Information System (SALI): the first IMS to integrate ESRI spatial datasets with an Oracle database (Clucas et al., 2002). We also, with seconded colleagues, developed the Environment for Natural Resource Information Integration (ENRII), which provided relevant standards, guidelines and protocols to achieve high-quality interpretation and integration across scales. Science in this framework can be integrated and linked to all-natural resource issues including those involving land, water, vegetation and climate. Through this tool, findings in one area can contribute to other natural resource understandings. The approach allows smart links, minimises duplication and provides pathways to improving management of natural resources across whole landscapes (Hynes, 2002; Hynes, 2004).

These projects were precursors to the current Globe and Ecosciences operating systems and platforms.

One Health for *Homo sapiens* and Other Species

One Health (OH) is a collaborative, multisectoral and transdisciplinary approach – working at local, regional, national and global levels – with the goal of achieving optimal health outcomes. It recognises the interconnections between people, animals, plants and their shared environment (Centers for Disease Control and Prevention (CDC, 2018; Alam & Chu, 2020).

Successful public health intervention requires the cooperation of human, animal and environmental health partners. Professionals in human health, animal health and environment and other areas of expertise need to communicate, collaborate on and coordinate activities. No one person, organisation or sector can address issues at the animal–human–environment interface alone.

OH is not new, but it has become more important in recent years and particularly at the present time with the devastating global impact of COVID-19. Many factors have changed the interactions between people, animals, plants and our environment in recent decades. Human populations are growing and continue to expand their geographic impacts. The Earth has experienced major physical and ecological changes, and this trend continues. The movement of people, animals and animal products has increased from international travel and trade. Diseases such as SARS, and presently COVID-19 (with SARS-CoV-2 being the causal virus), can now spread quickly across borders and globally (Centers for Disease Control and Prevention (CDC), 2018).

OH is a term that should not be used simply to describe obvious truths: that animals and humans can share diseases, or that environmental factors can influence the incidence of zoonoses. More importantly, it should galvanise us to look at ways to optimise clever upstream solutions to mitigate adverse health impacts (Salkeld, 2020). COVID-19 has laid bare the inadequacies in many societies and highlighted the injustices in minority groups worldwide.

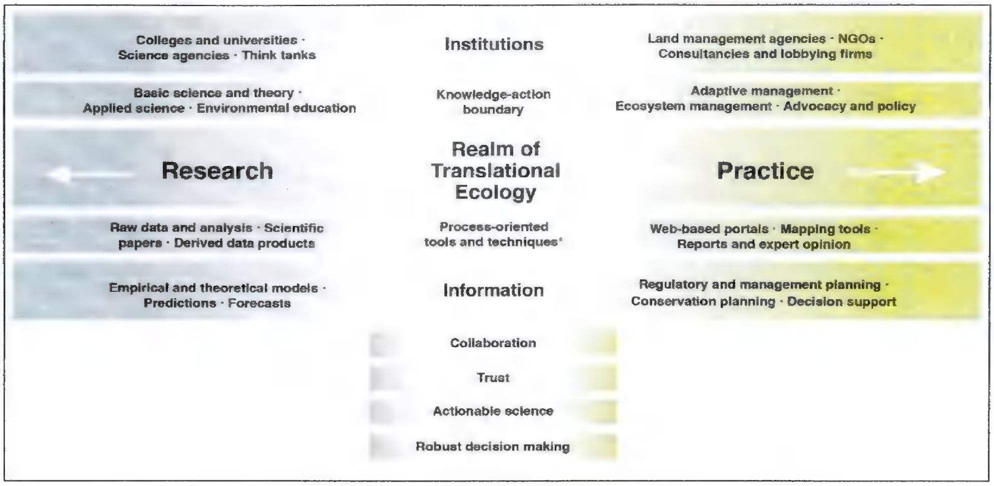
The year 2020 should be the start of a One Health global initiative, where social change, health and the environment begin to emerge as critical guiding lights for our global decision makers (Salkeld, 2020). OH epitomises a whole-systems approach, but perhaps would gain from a stronger and more versatile data management platform.

Professionally operated, big data management can effectively give *access to the right information at the right time for whole-systems-oriented solutions*. This capacity needs to be maximised in all three of the above network platforms and similar platforms to enable the efficient and relevant flow of information into research and community-linked methods that contribute to practicable sustainable outcomes.

Translational Ecology

Translational ecology is an emerging contemporary method that employs encompassing research strategies that can facilitate sustainable solutions and optimise inputs from professionally managed big data. "Translational ecology (TE) is an approach in which ecologists, stakeholders and decision makers work together to develop research that addresses the sociological, ecological and political contexts of an environmental problem" (Enquist et al., 2017). A TE strategy encapsulates an extended commitment to real-world outcomes. Effective TE increases the likelihood that ecological science will improve the decision making for environmental management and conservation (Enquist et al., 2017). The socio-ecological realm within which translational ecology operates is introduced in Figure 5.

Figure 5. The realm of translational ecology (TE). This is the nexus where knowledge meets action. It is situated at the intersection of a broad spectrum of institutions and information pathways where scientists, practitioners and stakeholders work together to build trust and to develop ideas, products and outcomes that are accessible and actionable, shaped by all participating parties, and can be readily used in decision making, scenario planning, structured decision making, climate adaption planning and other frameworks (after Enquist et al., 2017). M-LEA could positively contribute to this nexus.



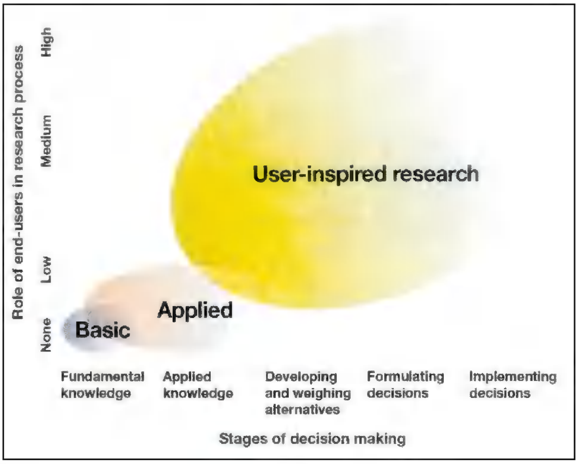
User-inspired TE can make research outcomes usable by and useful to decision makers (Wall et al., 2017). Barriers to the use of scientific information in decision making can be overcome by fostering social capital among collaborators, e.g. scientists, practitioners and members of the community. Relationships are fostered between groups through collaborative research opportunities, outreach and engagement activities. When participants openly acknowledge differences – in professional practices, expectations and rewards – a foundation for trust can be established. This is likely to increase the chances of successful collaboration. A well-articulated framework for managing engagement between ecologists, practitioners and other stakeholders increases the ability to identify mutually desired projects and assists in avoiding misunderstandings. Ecologists can avoid difficulties and improve the likelihood of effective scientist–stakeholder collaborative outcomes by consulting the body of successful case studies produced by science translators in ecology, public health and climate services (Wall et al., 2017).

The three research categories – basic, applied and user-inspired in relation to end-users and the types of decisions being made – are graphically represented in Figure 6.

Translational ecology must comprise more than clear speech, lexical equivalence and good intentions. To be effective, it requires understanding of the languages, cultures and currencies of policy, management and the societies in which relevant decisions are made. Translational ecologists need to understand the real-world contexts in which their science is applied; they must live simultaneously in two or more cultures. This is a field in ongoing development, but its perspectives can provide a capacity not only to identify and diagnose ecological afflictions, but also help treat or prevent them (Jackson et al., 2017).

Similar approaches have historically been incorporated in agricultural research and extension, but have less effectively accommodated the significance that agricultural and tree management practices have had on the long-term sustainability and values of the ecosystems within which they operate. We are now beginning to pay a price for this lack of awareness in terms of increasing native species extinctions, loss of whole habitats and increasing feral pests and noxious weeds.

Figure 6. Graphic representation of three categories of research – basic, applied and user-inspired – in relation to the roles and end-uses in the research process, and the types of decisions being made. For research results and other knowledge generated or co-developed to support decisions (i.e. management actions, policy decisions or programmatic development), there is often a need for greater involvement with potential end-users throughout the process (Wall et al., 2017). *Note*: This graphic is meant to provide the reader with a visual aid to compare the degree of engagement with end-users across a continuum of research approaches and does not represent an exact determination of the amount of research performed in each of these areas (Wall et al., 2017).



Concluding Remarks

In this paper I have sought to provide an overview of three themes: *Principles for a sustainable society*; *Understanding environmental systems and integrating both ecological and socio-economic processes*; and *Science through a big window – whole-systems science,* which seeks to focus and anchor the main themes of this thesis.

Principles for a Sustainable Society

The following principles will assist us in understanding how sustainable resource use will help maintain ecologically viable life systems (Court, 1990):

1. Sustainable development must grow from within a society. It cannot be superimposed from outside. Cultural integrity needs to be maintained.
2. Sustainable resource use (SRU) must maintain and restore biodiversity and employ sustainable resource use practices.
3. SRU explicitly values equity, provides the basic necessities of life and secures living conditions.
4. SRU will foster self-reliance and responsible local control over resources.
5. SRU will foster peace. (*This is a very difficult condition to satisfy in a presently mainly male-dominated world.*)

While governance for sustainable resource use must allow for mistakes, these should not endanger the integrity of ecosystems and their resource bases.

Understanding Environmental Systems and Integrating Both Ecological and Socio-economic Processes

The above principles need to be linked to research and management actions that address and embody the generic nature of sustainable resource management problems. Translational ecology offers a new paradigm in association with a whole-systems approach, which could effectively contribute to such links.

These frameworks recognise:

- The problems we face are essentially systems problems. Aspects of behaviour are complex and unpredictable. Causes are multiple.

Interdisciplinary, trans-disciplinary and integrated modes of inquiry are needed for understanding.
- They are fundamentally non-linear in causation. They demonstrate multi-stable states and discontinuous behaviour in time and space. *Here useful concepts come from non-linear dynamics and theories of complex systems* (Hollings, 1993).
- They are increasingly caused by slow changes reflecting accumulations of human influences on landscapes and seascapes. They can cause sudden changes in environmental variables affecting sustainability. *Analyses should focus on interactions between slow phenomena and fast ones, and monitoring should focus on long- to medium-term changes in key structural variables of their fluctuating environments* (Hollings, 1993).
- Spatial connections are intensifying so that problems are now fundamentally cross-scale in space and time. *The science needed is not only interdisciplinary but needs to be cross-scale. Multi-level analyses, hierarchical theory, spatial dynamics, event models, network analyses, remote sensing imagery, geographical information systems and parallel processing can assist in opening new ways to handle effectively analyses of more than two orders of magnitude. An understanding and application of the mathematics and modelling of emergent properties as a more powerful link between levels of scale above and below the systems investigated is essential*[3] (Hynes, 1978a; Hollings, 1993; Hynes, 2009; Hynes, 2015).

We have usually been able to achieve satisfactorily linkages between only two or three levels of scale up to the present. We must greatly improve on this performance.

The economical and sociological components, as well as the natural science components, of these problems have an evolutionary character. *The focus for natural science components relates to the dynamics of environmental and ecological change and is evolutionary. The best approach for economics and organizational theory is learning and innovation; and for policies, the best is adaptive designs that yield understanding as well as products* (Naveh, 1979; Hollings, 1993; Hynes, 1994; Hynes, 2009; Hynes, 2010; Hynes, 2011).

The complexities of issues concerning natural resource sustainability are emphasised here. We need to recognise and act on this fact.

Science Through a Big Window – Whole-systems Science

Whole-systems science seeks to draw together the most effective research strategies with regard to key elements of the above principles and understandings. Clearly this requires the judicious identification of multiple objectives and multiple hypotheses relevant to solving the specified system problem. I re-emphasise here that the solutions need to be cross-scale in space and time. Why? Because systems problems are complex, and behaviour is often unpredictable with non-linear causation in these dimensions. The solutions are likely to be beyond any single discipline.

By creatively and selectively employing methods from the toolkit overviewed in this address, we can perhaps for the first time start a more integrated scientific journey into how whole landscape or seascape systems function, one which can assist us to find more effective pathways towards sustainable resource management (Hynes, 2002; Hynes, 2004; Enquist, 2017; Wall, 2017; Jackson, 2017; Hynes, 2020). Time is of the essence here and the urgency immediate.

There is still at least one elephant left in the room. Good science requires good underlying theory, so both theoretical and practical themes need to go hand in hand. It is imperative that we invest serious ongoing effort into developing good theory to underpin whole-systems science.

Three Industrial Revolutions have traditionally been recognised, viz.: First – Coal and Steam, commencing about 1760; Second – Oil and Electricity, 1860s onwards; and Third – Computing, 1960s onwards. We are now experiencing the Fourth – Connected Technologies, 2020 onwards

[3] Ecological and environmental modelling of the systems under investigation can complement these approaches and can be very important in gaining understanding, but that is a subject for another paper.

(Ong, 2020). This is characterised by artificial intelligence, robotics, big data, smart technology, virtual reality, the internet of things and cloud computing, and can logically and effectively contribute to whole-systems science. These technologies when employed in whole-systems investigations are best achieved using highly skilled, cooperative teams, but even then, problems of scale will often demand collaboration with complementary interdisciplinary teams. The days of a solitary scientist working independently are becoming rarer. But invaluable theoretical breakthroughs can still arise from such work, as can ground-breaking traditional reductionist investigations that focus on key processes or specific component problems.

Acknowledging this, all inputs gain from judicious integration when seeking whole-systems solutions. The optimisation of connected technologies can play a fundamental role. Nevertheless, the problems are still system-level problems, and any component integrations need to be conducted in frameworks which, both theoretically and practically, provide the highest level of rigour possible. Crucial component sub-system investigations will need to run in parallel to enable whole-systems solutions. Denialists presently have relatively easy targets because the methodologies do not have theoretical and practical coherence, rational tests of connectedness and verifiable understanding of information-flow between levels of scale in space and time. It seems timely to now consider multi-level ecological analysis (M-LEA) or its contemporary derivatives as a methodology that could contribute to the development of a comprehensive theoretical framework for ecology, as well as providing an applied methodology. This is a paradigm that can strengthen and assist in the optimal use of big data and the IT tools now available to address whole-systems challenges. Further, the M-LEA framework could, I consider, assist in managing scale and information flow between levels. The paradigm could work effectively with TE. There is much work to be done. For the foregoing reasons there is a pressing urgency to invigorate and resource whole-systems science, if we are to contribute effectively and intelligently to solutions of the invidious problems facing humankind in the 21st century (Hynes, 2002; Hynes, 2004; Hynes, 2010; Hynes, 2020).

I watch with interest the currently operating Future Earth program (see Specht & Specht, 2020). This is a UN-associated, decade-long, multi-faceted, exciting international research and knowledge-action initiative, which has implemented a systems-based approach to global environmental and human sustainability challenges (Future Earth, 2020). It recognises our contemporary geologic epoch – the Anthropocene. I have not as yet identified the theoretical framework on which rigorous information flow of the outputs can be optimised by the Future Earth enterprise.

This address[4] has only skimmed the surface. Notwithstanding this, I hope I have sparked some interest regarding where ecological science needs to travel rapidly during this century. This disciplinary challenge needs to be successfully met if we are to contribute to relevant adjustments, crucial to the human use of resources, population stabilisation and pollution management for our species and our increasingly vulnerable biosphere, and survive sustainably with integrity into the 22nd century. However, convincing governments, bureaucracies and the wider community of the urgency and necessity of this need may be the biggest challenge of all.

[4] Hopefully I can explore some of these needs and approaches in relation to scale and information integration in a more detailed paper for our 2021 *Proceedings*.

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Royal Society of Queensland Annual Report 2019–2020

Overview

This report covers the period from 16 November 2019 to 15 November 2020. The nearly 12 months have experienced extraordinary circumstances which we could not have foreseen at the time of the Annual General Meeting in November 2019. However, in 2020 some major achievements were accomplished and milestones reached. Instead of organising events, the office-bearers of the Society have focused their attention on publication of the annual peer-reviewed *Proceedings*, two Special Issues and the Rangelands Policy Dialogue. This has been an impediment to hosting activities that might appeal to the complete range of interests of members.

Just as Council reported last year, the Society remains in excellent intellectual health but precarious financial health.

Corporate Affairs

During the year, the continued engagement of Mrs Pam Lauder as part-time (2–3 hours per week) Administration Coordinator and Mr John Tennock on a retainer as Webmaster for both the Society's website and the Queensland Science Network (QSN) website has maintained the Society's administrative capacity. Mr Tony Van Der Ark has continued as Membership Coordinator and Dr Ann-Marie Smit as Royal Society Newsletter Coordinator. Mr Col Lynam joined the administrative team as founding Editor of the Queensland Science Network Newsletter.

Royal Society of Queensland Council

The Council elected at the Annual General Meeting comprised Em. Prof. Angela Arthington as Honorary Editor, Dr Paul Bell, Dr Geoff Edwards as Vice-President – Communications and Policy, Mr Andy Grodecki, Mr James Hansen as Secretary, Dr Ross Hynes as President, Assoc. Prof. Trevor Love, Dr Joseph McDowall as Treasurer, and Ms Revel Pointon. Mr Craig Walton retired as Immediate Past President.

Face-to-face meetings of Council were held on 18 December 2019 and 7 January 2020. One meeting was held by Zoom on 24 July. The vast bulk of issues are debated via email traffic, telephone and Zoom.

Finances

The Society continues to draw down its accumulated reserves in order to fund its current activities. The officers have been unsuccessful in securing significant general-purpose sponsorship.

The Society opened a new bank account with Bank Australia, as the Commonwealth Bank was unable to provide a satisfactory Internet banking service.

The Society gained public liability insurance coverage as a member of Queensland Water and Land Carers.

Library

Ms Shannon Robinson, Queensland Museum's Librarian, continued in her role as the Society's Honorary Librarian and continued to advise the Society on library matters.

Membership Roll

At 1 November 2020, the Society has 132 paid-up and honorary members, with about 25 others due for renewal. There are six Honorary Life Members: Dr A. Bailey, Dr J. S. Jell, Dr J. O'Hagan, Ms C. Melzer, Prof. C. Rose and Em. Prof. R. Specht. Former President Mr Craig Walton and long-standing member Prof. Dilwyn Griffiths accepted offers to be invested as Life Members, but the investiture ceremonies have not yet been held.

Annual General Meeting – 28 November 2019

The Annual General Meeting of the Society was held in the Community Meeting Room of the

Brisbane City Council, Brisbane Square, Adelaide Street.

Awards

Em. Prof. Ray Specht was awarded an Order of Australia in the January 2020 Australia Day awards.

Early in 2020, Mr Harry Van Der Ark was advised that his application to attend Harvard University's Pre-College Summer Program had been accepted. Fifteen students from around the world were to be living on campus under the supervision of Prof. Cari Cessaroti to study the fundamentals of particle physics. The program was shifted online, and Harry completed the 16-day course.

Em. Prof. Ian Lowe was awarded a Doctor of Science by the University of New South Wales in December 2019.

Prof. Sean Ulm was elected to the Council of the Australian Academy of the Humanities for a two-year term in November 2019.

In October 2020, a news item on the ABC announced that Dr Geoff Monteith, eminent Queensland entomologist and long-standing member of the Royal Society, had been placed on a list of the world's top 10 most commemorated scientists, which includes Charles Darwin, with more than 200 species named in his honour.

Members' Interests Page

During the year, a list of members with their fields of particular interest was included on the "Members Only" page of our website. The purpose is to allow members to identify other members with scholarly or curiosity-led interests matching their own. This page is accessible only by financial members of the Society via a password-protected login. Other than at events, which have been held over in 2020, the primary vehicle for networking has been email traffic steered through and coordinated by a small number of office-bearers. The intention of the new Members Only section is to decentralise networking so that all members can be active agents of and beneficiaries of the rich resource that is the knowledge of the membership.

Council resolved to include members in the list on an opt-in basis. However, few members have taken advantage of this opportunity.

Publications

Proceedings of The Royal Society of Queensland

History was made on 18 February when for the first time an entire volume of the *Proceedings of The Royal Society of Queensland* was placed online under open access conditions. This was Volume 125, *The Land of Clouds Revisited: The Biodiversity and Ecology of the Eungella Rainforests*, edited by Guest Editor Prof. Roger Kitching of Griffith University. Print-publication of this volume followed through generous sponsorship from the Environmental Futures Research Institute of Griffith University, the Reef Catchments NRM body and an anonymous philanthropist.

Then, for the first time in the Society's history, the annual *Proceedings*, Volume 124, was published online under open access conditions. Further, papers were published online as soon as they were typeset after acceptance, and sent to the printer after the entire compilation was complete. Open access will bring a financial penalty as the Society will no longer receive copyright fees, but Council has considered that the move will improve the profile of the journal and lead to more citations for its authors.

Volume 124 was produced in turn by Dr Paul Bell for a short period, then Mr Diogenes Antille, and when he was unable to continue, completed by the President, Vice-President and Ms Revel Pointon as joint co-Editors. The changeover caused a significant delay in appearance of the volume. Although the first article was published (online) within the usual time frame of December 2019, the final paper was not published until June 2020.

The year marked another milestone in that four Special Issues are published or in preparation: Volume 125 (*The Land of Clouds Revisited*, edited by Em. Prof. Roger Kitching); Volume 126 (*Springs of the Great Artesian Basin*), with Em. Prof. Angela Arthington as lead Editor; and Volume 127 (*A Rangelands Dialogue: Towards a sustainable future*), edited by Dr Paul Sattler with Dr Ross Hynes and Dr Geoff Edwards as contributing editors. A Special Issue on preventative health has been foreshadowed but will be delayed. Volumes 125 and 127 have already been printed, and Volumes 126 (Springs) and 128 (annual *Proceedings*) are on track to be completed and printed by the end of the year.

Contributions of $9000, $15,000 and $2000 have been gratefully received from the Queensland Department of Natural Resources, Mines and Energy, the Commonwealth Department of Agriculture, Water and the Environment, and Griffith University's Australian Rivers Institute, respectively, to print the Special Issue on springs of the Great Artesian Basin. The Commonwealth grant allowed the Society to host a session at the Australasian Groundwater Conference (AGC 2019), held in Brisbane in November 2019 and facilitated by Em. Prof. Angela Arthington.

An anonymous donation has paid for the cost of printing a small number of copies of Volume 127 to satisfy statutory deposits and to give copies to authors and reviewers.

The Society is grateful for the generosity of those institutions and anonymous individuals who have enabled three volumes to be printed. This is testament to the significance of our long-standing journal and to the value of publishing knowledge in printed form.

The Society engaged a new typesetter, Mr Darryl Nixon of Sunset Publishing Services, who has given meticulous attention to typography beyond commercial expectations.

Newsletters

Eighteen Members' Newsletters (including intermediate Notifications) were produced during the reporting period, against a target of monthly. With No. 7, a system of numbering each year's Newsletters sequentially was instituted and the distinction between the Newsletters and intermediate Notifications was abandoned. Dr Anne-Marie Smit took leave of absence from her position of Newsletter Editor for a period but anticipated resuming the vital role during the new Council year. These Newsletters are privileged to members. During the year, the Society's Webmaster Mr John Tennock uploaded the archive of previous Newsletters to the Members Only section of the website.

On 1 August the first issue of a Newsletter for the Queensland Science Network was completed, and then another on 15 October. The intention is that the Royal Society Members' Newsletters will be largely focused on the activities of members and external events of particular relevance to Society activities; the QSN Newsletter would be substantially broader in scope, covering the activities of the 26 member groups and their members in particular, but matters of general science interest as well.

The QSN Newsletter was distributed to leaders of the member groups with an invitation to pass it on to their mailing lists, but was also published on the QSN website (https://scienceqld.org/category/member-groups/) with a subscribe button allowing the general public to join a subscription list.

The method of distribution changed during the year. Previously, Newsletters were emailed as PDFs. This is suboptimal from an IT point of view for several technical reasons. Latterly, an email has been sent to members with a link to an unpublicised page on the RSQ website from which a PDF can be downloaded. It seems likely (from automated statistics) that this two-step process has caused a decrease in the number of members who have accessed the Newsletter. Feedback from members is required as to the best method of distributing this information.

Members' Publications

Apart from journal articles, two substantial book-length works by members were published during the AGM–AGM year:

- Dr Philippa England has published a new edition of her landmark book *Planning in Queensland: Law, Policy and Practice*, with Dr Amy McInerney (The Federation Press).
- Prof. Dilwyn Griffiths published a new work *Tropical Ecosystems in Australia: Responses to a Changing World* (CRC Press).

Although the Society takes no credit for these works, we hope to strengthen the intellectual environment in which our members feel confident to put their knowledge into print.

Education Project

No progress was made during the year on development of new materials for the senior Queensland science curriculum as no funding was secured.

Events and Activities

Apart from the Annual General Meeting in November 2019, the only event held was an online Members' Networking Teleconference on 24 September. The World Science Festival was cancelled.

An event "Is Queensland prepared for a warming climate?", organised for 6 April jointly with the Royal Geographical Society of Queensland and Griffith University's Centre for Governance and Public Policy, was cancelled because of the health restrictions on meetings proclaimed by the Queensland Government.

Rangelands Policy Dialogue

Following the July 2019 Rangelands Policy Dialogue meeting in Brisbane, the Society established a Rangelands Discussion Group on behalf of the three-way collaboration with AgForce and NRM Regions Queensland: https://groups.io/g/rangelands-dialogue. By early November, some 750 messages had been posted to the group, covering a range of subjects including some with highly original and thoughtful insights. An Issues Paper itemising some 35 significant issues was distributed to the participants. A pause was called on the discussion forum to allow participants to respond to the Issues Paper and to allow the Society to consider the most appropriate process to carry the Dialogue forward.

During the year, NRM Regions Queensland allocated funds to host two regional workshops to bring the Dialogue to the attention of pastoralists not otherwise engaged and to seek their views about the significant issues identified. A sum of $6000 was paid to the Society to fund the preparation of three background research briefs that would summarise the scholarly literature in the fields of economics, regional development and challenges on the horizon. Four substantial papers were delivered by the due date, 27 October, and two others are at an advanced stage of preparation.

On 2 October, the Committee on Agriculture of the Food and Agriculture Organization of the United Nations network endorsed a proposal by the Government of Mongolia to designate an International Year of Rangelands and Pastoralists. The Royal Society of Queensland had given its support along with the Australian Rangelands Society, the only other Australian NGO to do so, and the Australian Government.

Restore Australia Initiative

During the year, a submission was crafted for funding under the Restore Australia program to allow the Society to lead a significant program of policy analysis related to the central and southern Queensland rangelands and a large tract of the slopes and western rangelands of New South Wales. The initiative is proposed to be funded by international philanthropists. Advice is awaited.

Commentary

Queensland Country Life extended its invitation to submit a regular column under its "View from the Paddock" series of opinion pieces. Columns were published on 7 February, 2 April, 5 June, 20 August and 29 October 2020. The Society is grateful to the Editor for allowing this opportunity to present opinions on behalf of Queensland's scientists. All articles were printed without significant editorial amendment.

RSQ and QSN Websites

As a general policy, the Society's website is reserved for activities and publications by the Society and its members. The QSN website presents a wider range of general science activities and materials, largely (but not rigidly) confined to the activities of its member groups. The QSN website includes links to some other sites of general science interest such as the Events Calendar of Inspiring Australia – Queensland.

Five members took advantage during the year of the opportunity to open a page for their field of interest. This opportunity is available free of charge to all members:

- Dr Philippa England and Dr Nelson Quinn – conservation covenants
- Mr Colin Lynam – earthquakes and tsunamis
- Dr Elwyn Hegarty – Mr F. A. Perkins
- Mr Steve Hutcheon – Spanish exploration of northern Australia

The Society's website, along with the QSN website, is soon to be migrated from the server of its *pro bono* developer to the Society's own host, HostPapa.com. It is likely that access to the archive of *Proceedings* will be slower in future because the full-text search facility requires large server capacity. We place on record our sincere thanks to Mr Joseph Listo of ClearMedia and his principals for developing our site, adding an automated membership facility and maintaining the site for the past four years.

Research Fund

Consistent with the commitment in 2018 to fund grants in three successive years, a third round of grants to a value of $5000 was announced, to close on 28 November. This year the Funding Policy was amended to encourage applications from citizen science practitioners. The capital reserve of $40,000 remains intact.

Royal Societies of Australia

The Royal Societies of Australia has commenced preparation for a significant event on "Stewardship of Country". Plans to hold the event in October 2020 were disrupted by virus-based restrictions. The steering committee, which includes representatives of the Society, has obtained commitments from a most attractive set of speakers and is scheduling the event (whether face-to-face or online) for early in the New Year.

Final Words

Whereas 2020 has been an extraordinary year, we offer warm thanks to all members who have contributed positively to ensuring it has been a very productive one. We commend to members the valiant and ongoing efforts of our voluntary honorary office-bearers, our current Councillors and Editors, who have worked tirelessly to keep the ball rolling and on track in these difficult times. Their assistance, valuable perspectives and ideas to secure the Society's immediate and longer-term future of publication of scientific works, online and in print, have been greatly appreciated.

We would like to re-emphasise that, remarkably, by year's end five volumes of the *Proceedings* will have been published. We offer special thanks to our Honorary Editor, Em. Prof. Angela Arthington, for facilitating this success. These volumes are now available in digital form for the first time. They include two annual editions, viz. Volumes 124 and 128, and three Special Issues (Volumes 125, 126, 127). We have used video conferencing where practicable and have published a monthly web-based Newsletter.

On behalf of all RSQ members, we extend our thanks to all who have been involved and hope that the future will bring opportunities to restore and introduce more activities for our vibrant Society.

Geoff Edwards and James Hansen
Date: 15 November 2020

The Royal Society of Queensland Research Fund

Several years ago, the Central Queensland Koala Volunteers expressed a desire to establish an ongoing Trust Fund to sponsor Central Queensland-related research into koalas and associated environmental subjects. The Volunteers chose the Royal Society as a partner in this venture, given the Society's long-standing history and its mandate to encourage and promote science. The Society welcomed this offer warmly as it is consistent with the Society's position as a learned society with an enduring life and offering a vehicle (the *Proceedings*) for publishing the findings of quality research. The Trust Fund allows the Society to offer a complete service to researchers, from funding their investigations, through mentoring, hosting events and publicity, to publication of completed research.

The Volunteers donated the first contributions totalling $10,000 to the Fund to establish a basis for seeking donations. This was matched by the Society from its general account. The Australian Taxation Office granted tax deductibility, and the Fund was registered as a charity on 25 July 2014. The Fund was launched by Her Excellency the Governor of Queensland, Penelope Wensley AC, at a reception held at the Queensland Museum on 13 June 2014.

It was not until donations were received from philanthropists to push the capital fund beyond $50,000 that applications were opened. As Trustee of the Fund, the Council of the Royal Society determined to commit $5000 for each of three years to research grants. Some 50 people gathered at the Centre for Biodiversity and Conservation Science, University of Queensland, on 5 June 2018 when the inaugural round of applications was launched by late Life Member Emeritus Professor Trevor Clifford. The Treasurer of the Central Queensland Koala Volunteers, Miss Shirley Hopkins, flew from Rockhampton for the day.

Inaugural Grant Round 2018

Following assessment by a three-person panel of experienced scientists from institutions other than those of the applicants, the winners of the first two awards were announced formally at the 2018 Annual General Meeting by Life Member Emeritus Professor Calvin Rose. The two awardees gave PowerPoint presentations (available on the RSQ website: http://www.royalsocietyqld.org/research/).

- Alex Jiang. Humble cow: a koala serial killer? An investigation of koala-cattle interactions.
- Chapa Gimhani Manwaduge. Conservation Biology of Threatened Native Olives (Genus *Notelaea*) in Southern Queensland.

Grant Round 2, 2019

Again, following independent assessment against the selection criteria, the applications judged most meritorious were both for work on the koala. The Australian Koala Foundation generously agreed to fund one of the highest-ranked applications, which enabled the Society to issue a second grant. The two candidates gave presentations immediately after the Annual General Meeting in November 2019.

- Dr Michaela Blyton. What Do Koalas Eat Where and Does This Shape Their Microbiomes?
- Dr Bonnie Quigley. Comparing Koala Retrovirus Infection between Central and South East Queensland Koalas.

Grant Round 3, 2020

Applications were invited for grants from the Research Fund, which closed at midnight on 28 November 2020, under fresh guidelines. The new 2020 Funding Policy encourages applications from citizen science groups. Further details can be viewed at http://www.royalsocietyqld.org/research/

Fund Details

To preserve the capital reserve, no further rounds will be launched unless donations can be received to augment the Fund. Donations can be lodged at any time into the trust account:
BSB 064-001, Account number 11970213. Deposits can be made at any branch of the Commonwealth Bank or online. The Australian Business Number for the Trust Fund is 33 120 792 616.

Royal Society of Queensland Research Project Reports 2018–2019

Humble Cow: A Koala Serial Killer?

Royal Society of Queensland Research Project, 2018

Alex Jiang[1]

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Background to Project

Koala (*Phascolarctos cinereus*) populations are declining in Australia, with habitat loss believed to be one of the major factors leading to this decline (Seabrook et al., 2003; McAlpine et al., 2006). In Queensland, clearing of koala habitat in coastal zones is mainly associated with urban development, while in rural areas of Central Queensland it is associated with the expansion of cattle grazing from the beef and dairy industries (Preece, 2007). Consequently, research is urgently required into the potential conflicts between cattle and koalas to guide management strategies which will enable cattle and koalas to co-exist. The recent concept of 'Koala Beef' is intended to encourage the conservation of koalas in cattle grazing land by developing a koala-friendly beef industry (Ellis et al., 2017). Koala Beef encourages the preservation of remnant bush as koala habitat on grazing properties, with vegetation corridors to connect these habitat remnants so that resident koalas are able to survive and traverse to new areas safely, while maintaining the economic profitability of the cattle property.

Study Area

The University of Queensland is conducting a broad-ranging koala research program (the Hidden Vale Koala Project – HVKP) on a large private property, referred to as Hidden Vale and located in South East Queensland. Approximately 75% of this property is Nature Refuge, but it also includes beef cattle farming, extensive mountain bike trails and an ecotourism resort. The main focus of the HVKP is the investigation of the abundance, distribution, disease prevalence, fecundity and mortality of the koala population in this area.

The HVKP property includes a large area of koala habitat which is also grazed by free-range cattle herds. Therefore, as part of the broader HVKP, it offers a valuable opportunity to investigate the potential koala–cattle interaction issues raised in inland Central Queensland.

Objectives of the Research

The objectives of the research funded by The Royal Society of Queensland are to:

(1) investigate the scale and frequency of cattle-inflicted injuries/deaths to koalas via a nation-wide online survey;
(2) test cattle reactions towards koalas by the use of a koala model mounted on a motorised vehicle; and
(3) investigate the impact of cattle on koala movements and hence their home ranges, including variations in location and size.

The assumption is that if the presence of cattle in koala habitat has adverse effects on free-ranging koala populations:

(a) cattle would be found to be a significant cause of injury or death of koalas;
(b) cattle would be found to display aggressive behaviour towards the koala model; and
(c) the home ranges of koalas would decrease in size or they would move away to avoid potential contact with the cattle.

Implications for Koala Conservation

The findings of this study will have several important implications for koala conservation in rural areas, especially in Central Queensland where the overlap of koala home ranges and cattle grazing is extensive compared to coastal areas. Findings of the research may assist koala conservation in the following ways:

1. Guiding koala conservation and mitigation management strategies. Extra monitoring and preventative approaches may be required to manage the potential adverse impacts when a koala population's home range overlaps with cattle grazing land.
2. Alerting cattle farmers in respect to the potential threat of domestic cattle on local koala populations and advising changes to their cattle management procedures which might minimise such risks.
3. Establishing the theoretical basis of the Koala Beef project, the aim of which would be to identify koala-friendly farm management strategies and protocols.

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Conservation Biology of Threatened Native Olives (Genus *Notelaea*) in Southern Queensland

Royal Society of Queensland Research Project, 2018

Chapa Manwaduge[1], Matthew Phillips[1], and Susan Fuller[1]

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Background to Project

The genus *Notelaea* (family Oleaceae) is endemic to Australia and consists of 12 species. One of these species, *Notelaea lloydii*, is listed as vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999) and the Queensland *Nature Conservation Act 1992* due to its restricted distribution encompassing approximately 3700 km^2 in South East Queensland (Conservation Advice for *Notelaea lloydii*, 2008; *Nature Conservation (Wildlife Management) Regulation 2006*, 2017). *Notelaea lloydii* occurs in about five small disjunct populations, each with fewer than 30 individuals, together with a few other individuals scattered along roadsides (Queensland Herbarium records and personal observations). Given the high degree of urbanisation and vegetation clearance in South East Queensland, it is possible that intraspecific gene flow is limited between these small and isolated populations and inbreeding may be a significant risk. Consequently, it is essential that an evaluation of the levels of genetic diversity within populations and the genetic differentiation and gene flow among populations is undertaken to inform conservation management strategies.

Furthermore, *N. lloydii* occurs in sympatry at the only site where the critically endangered *N. ipsviciensis* is found. *Notelaea ipsviciensis* exhibits intermediate morphology between *N. lloydii* and *N ovata*, raising speculation that it is a natural hybrid of the two (Beyleveld, 2006; Harris, 2004). Both *N. lloydii* and *N. ovata* have overlapping flowering periods, further increasing the possibility of inter-species gene flow. Such hybridisation can place a rare species at an increased risk of extinction through genetic swamping (Ellstrand & Elam, 1993; Levin et al., 1996). If hybrids do not exhibit reduced fitness relative to parental taxa, they may ultimately displace pure populations of one or both parental taxa. Therefore, it is of critical conservation importance to evaluate the levels of genetic diversity and genetic structure of *N. lloydii* population at the site where it is sympatric with *N. ipsviciensis*, to determine whether it is at risk of extinction due to displacement by this potential hybrid.

Genetic data (SNPs) have been obtained for a small number of samples and populations of *N. lloydii*, and preliminary results indicate little genetic structure among *N. lloydii* populations. Further sampling is required to improve resolution, and a comparative population genetics study with a common *Notelaea* species is required to understand the relative genetic diversity and inbreeding among the *N. lloydii* populations, Furthermore, the inclusion of other *Notelaea* species will allow systematic uncertainties to be resolved.

Project Significance

When a rare plant species is known to exist only in small and isolated populations threatened by urban development and land clearing, it is critical to have a good understanding of the levels of genetic diversity and gene flow to enable effective conservation management strategies to be developed. In such situations, protecting only the habitat may not ensure the long-time survival of the species. It may be

necessary to intervene through strategies such as augmentation, re-introduction and translocation to ensure the viability of *N. lloydii* into the future, and this should be undertaken only once a thorough understanding of the conservation genetics of the species has been obtained.

Objectives of the Research

The aim of this project is to examine the levels and patterns of genetic diversity within and among the remnant populations of rare *N. lloydii* and common *N. longifolia*, as well as resolving taxonomic uncertainties within the genus *Notelaea*.

Research Outcomes

Our genome-wide SNP data does not support *N. ipsviciensis* as a distinct species but a natural hybrid, raising doubts whether it should be given conservation priority. Also, the SNP phylogeny which includes all the known *Notelaea* spp. indicates that *N. lloydii* forms a monophyletic clade including *N. microcarpa*, suggesting that the two taxa may constitute a single species. Nevertheless, our comparative population genetic analysis has revealed a high degree of genetic structure among the fragmented *N. lloydii* populations and high levels of inbreeding compared to the more common *N. longifolia*, emphasising the necessity of a broad conservation approach going beyond the species level.

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What Do Koalas Eat Where, and Does This Shape Their Microbiomes?

Royal Society of Queensland Research Project, 2019

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Background and Significance of the Research

Throughout their wide geographic range, koalas (*Phascolarctos cinereus*) always eat *Eucalyptus* leaves. Few animals can stomach, let alone survive, on these fibrous, toxic leaves, and koalas are thought to rely on their gut microbiomes to help them digest their nutritionally poor diets. Our research has revealed that the microbes that make up the koala's gut microbiomes vary over their range, with koalas from proximate populations having more similar microbiomes compared to koalas from opposite ends of the continent. These patterns extend to the microbes' ability to break down and make different compounds, thereby potentially influencing the koala's nutrition. Our work suggests that climate and dispersal patterns play a role in shaping these patterns, but we don't know how diet is involved.

Within one population we found that individuals that feed on different eucalypts have distinctive microbiomes, while those with similar diets have similar microbiomes. Yet, the microbiomes of koalas on St. Bees Island differ from those on North Stradbroke Island, despite koalas on both islands reportedly feeding on *Eucalyptus tereticornis*. By contrast, koalas at Clermont, Surat and Gunnedah have similar microbiomes and are thought to have similar diets. To resolve these discrepancies we need accurate information on which *Eucalyptus* species the koalas are eating.

Objectives and Implications

This study will leverage extensive pre-existing data, samples and significant prior funding to determine how the species and nutritional composition of the koala diets affect the composition and function of their microbiomes across populations. To do this we will identify which species of *Eucalyptus* koalas are eating at sites across Australia, including St. Bees Island and Clermont in Central Queensland.

A better understanding of koala diets will assist identification, conservation and restoration of their habitat. Further, understanding how koala diets interact with the microbiome to influence koala nutrition is vital to assist rehabilitation and translocation of koalas.

Approach and Study Design

We will characterise the diet (*Eucalyptus* species eaten) of 187 koalas from 20 populations across four states. This will allow us to compare koala diets across the country and to connect koala nutrition and microbiome composition. The nutritional composition of the koalas' diets will be determined from data on the chemical make-up of the eaten eucalypt species. This information will be combined with existing data on the composition and function of the animals' microbiomes.

As part of a completed ARC grant, we have already collected the required samples and characterised the koalas' microbiomes by shotgun sequencing of DNA extracted from faecal pellets. We have also characterised the nutritional composition of candidate eucalypt species from the areas where the koalas were sampled, using near-infrared spectrometry (NIRS) and chemical analysis. However, determining the composition of the koalas' diets was beyond the scope of that project and required the development of new genetic techniques.

Identifying what koalas eat in different parts of the country is trickier to answer than one might think. For one, koalas often feed at night in different trees from those that they rest in during the day, making direct observations difficult and labour intensive. Other researchers have used microhistological analysis of leaf cuticle fragments and chemical analysis of hydrocarbon cuticle waxes from faecal pellets to reconstruct diets, but neither method is able to differentiate between many eucalypt species. Standard genetic approaches to faecal diet analysis (e.g. DNA barcoding) do not work for eucalypts due to their genetic similarity. We have developed a new approach that utilises state-of-the-art next-generation sequencing to characterise koala diet composition.

Investigators

Dr Michaela Blyton, a Research Fellow at The University of Queensland, will be the chief investigator on this project and will undertake the primary data analysis. Dr Ben Moore, a senior lecturer at Western Sydney University, will contribute to data interpretation and manuscript preparation in his role as co-investigator.

Acknowledgement

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Comparing Koala Retrovirus Infection Between Central and South East Queensland Koalas

Royal Society of Queensland Research Project, 2019

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Background and Significance

The survival of the koala (*Phascolarctos cinereus*) is under serious threat, with this iconic marsupial declared "vulnerable" by the Australian government in 2012. A major contributor to this decline is disease, with *Chlamydia* widely recognised as the major infectious threat, and the relatively recently discovered retrovirus, Koala Retrovirus (KoRV), a threat itself and worse when combined with *Chlamydia*. KoRV is from the same family of viruses as HIV and has been detected in all South East Queensland koalas tested to date (Quigley et al., 2018). Currently, seven subtypes of KoRV (A-I) are recognised, and KoRV-B infection is significantly linked to chlamydial disease and cancer deaths in koalas from South East Queensland (Quigley et al., 2018; Chappell et al., 2017). However, similar testing has not been conducted in other parts of Queensland. Testing location is important, as genetic analysis of Queensland koalas revealed two different lineages of koalas co-occurring north of Brisbane, with possible biogeographic barriers at the St Lawrence Gap (near Rockhampton) and the Brisbane Valley (at Brisbane) (Neaves et al., 2016; Bryant & Krosch, 2016). This suggests that it may not be accurate to extrapolate test results from koalas around Brisbane to koalas north of Rockhampton. With strong evidence that KoRV is involved in very serious koala health conditions, it is time for focused research into KoRV across Queensland.

Objective

The objective of this study is to determine the prevalence and diversity of all seven subtypes of KoRV in two distinct areas of Queensland. We will evaluate whether there are differences in KoRV between South East Queensland koalas and Central Queensland koalas that could affect management practices (like relocating koalas) between these areas.

We expect all Queensland koalas to be infected with at least one KoRV subtype; however, we anticipate different patterns in virus diversity between the biogeographical barriers. Learning how these patterns differ between koalas will be important for KoRV vaccine development (under way by the USC research team) and will inform *Chlamydia* treatment and koala translocation strategies across Queensland.

Investigators

Dr Bonnie Quigley, University of the Sunshine Coast, is a post-doctoral research fellow with 12 years' experience in microbiology research. Dr Quigley currently works with Prof. Peter Timms, a world-leading expert on chlamydial disease and vaccination in koalas.

Dr Alistair Melzer is an established koala ecologist and research program leader of the Koala Research Centre of Central Queensland at CQU.

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James C. Galletly

Baseflow in the Lockyer Creek

James C. Galletly
M Agr Sc, University of Queensland

A thesis submitted for the degree of Doctor of Philosophy

School of Land, Crop and Food Sciences
and
School of Natural and Rural Systems Management
University of Queensland, Gatton, Australia
2007

Abstract

The basic question which this thesis seeks to answer is: 'Was the baseflow which flowed continuously in Lockyer Creek prior to 1980 outflow from adjacent alluvial aquifers, or was it outflow from basalt aquifers on the Main Range?' This question was not obvious at the start of the project when information from 'official sources' suggested that Lockyer Creek was ephemeral, and there was no baseflow.

To answer this question, it was necessary to define baseflow (as outflow from aquifers) and to devise a means of separating it from overland flow, because the existing methods separate 'quick flow' from 'prolonged flow'; not overland flow from baseflow. The existence of baseflow presumes the existence of aquifers in the catchment, so geology of the catchment was examined to identify its aquifers.

Streamflow records at four sites: three upstream and one downstream, were analysed to establish that baseflow was a significant component (25%) of streamflow over the period 1910–2000, and that average baseflow over this period was close to the estimated long-term safe yield of the Lockyer alluvium. The process of aquifer recharge was analysed and it was concluded that the alluvial aquifers are recharged by infiltration of water mainly through the bed of creeks and saturated flow in the aquifer below the water table, followed by unsaturated flow across a saturated/unsaturated boundary at the wetting front.

Saturated flow is driven by the hydraulic gradient on the water table (which was shown in 1949 to slope away from creeks), while unsaturated flow is driven by the matric potential across the wet and dry sides of the wetting front. Unsaturated flow is orders of magnitude slower than saturated flow, but takes place over a much greater area than saturated flow. Because it is such a slow process, long duration flows are required to achieve significant aquifer recharge.

Chemical analyses of water from basalt aquifers, baseflow and alluvial aquifers confirmed that the 'ionic signature' of the three waters was similar, which would be expected if baseflow was outflow from basalt aquifers, which in turn recharged alluvial aquifers. The ionic signature of water in the adjacent sandstones is quite different from that of these three waters. Ions present in water in the alluvium, including the sodium ions, are therefore consistent with the idea of the basalt water being concentrated by evaporation and/or evapotranspiration. It was concluded that water use by phreatophytes (historically) and irrigation (recently) was largely responsible for the slope on the water table in aquifers (towards aquifer margins).

Since the commencement of irrigation, flow duration in Lockyer Creek has progressively decreased, and the depth of water in alluvial aquifers has also declined, indicating that, in many years since 1937, the rate of water use for irrigation has exceeded the rate at which water was supplied by the catchment.

The water in alluvial aquifers is derived from baseflow which, in the Lockyer Valley, is outflow from basalt aquifers in the Main Range, not from adjacent alluvial aquifers. The water is not infiltration from rainfall, bank flow or cross-formational flow from adjacent sandstones as is often reported in the literature. This new understanding should be useful in devising a strategy for managing irrigation water use in the Valley as part of an integrated catchment-management strategy.

Obituary for Dr James Craig Galletly

24 August 1927 – 5 June 2020

One of Australia's Great Water Champions

Born in Warwick on 24 August 1927 just before the Great Depression, Jim (James Craig) Galletly's early life was one of disruption and substantial poverty for his parents Janet and Stewart, and for Jim and his four older siblings Neil, Stewart, Jean and Naomi. Stewart Galletly, a trained UK metal draughtsman and model maker who helped lay the keel of the Titanic, and art and physics teacher Janet McKelvie from Undulla Station west of Tara, met when Stewart was posted to the Miles area as a Presbyterian Bush Brother. Marrying in 1915 the day before the Gallipoli landing, Jim's parents struggled for survival despite their skills and education, beginning their family life on a property at Culgara near Undulla at the time prickly pear was rendering thousands of hectares of country unproductive. They moved for work to Warwick, Glen Innes, and then on to Woodridge – firstly living in a 'bag palace' with bark roof, bag walls and a dirt floor, and then in a more substantial pise dwelling built from materials on site by Stewart Galletly, which featured in the *Queensland Agricultural Journal*, 1 August 1937. To supplement their income they milked a few cows, with Jim delivering cream to the Kingston factory on his bike.

Eventually, with a small inheritance and the slow return of national prosperity, the family purchased a dairy farm at Mount Larcom, milking 40 Jersey and AIS cows to supply cream to Port Curtis Dairy. Jim enjoyed working and living on the dairy farm, noting the healthy year-round flow and perch numbers in the creek he crossed on his way to school every day. With his early schooling interrupted several times by family moves and attending country schools with limited grades, Jim finally completed Grades 4 to 7 at the one-teacher Machine Creek School outside Mt Larcom. In 1942 at the age of 15, Jim was one of a select few Queensland school students to pass the Scholarship exam, enabling him to attend Queensland Agricultural High School and College at Gatton from 1943 to 1946.

This was the start of a lifelong association with the college. Conditions were basic in 1943, with the main college buildings being used as a US

Army base hospital, but Jim excelled. Dux of his class each year, he was good at sports – boxing and cross-country – and enjoyed the large practical component of college courses. Jim recalled planting 10 acres of opium poppies to supply the hospital with medicinal heroin. In 1946, as one of only two students to win open scholarships to The University of Queensland, Jim unsurprisingly chose agriculture, completing his degree in 1950.

Jim's Bachelor of Agricultural Science led to work as a soil conservationist with the Queensland Department of Agriculture and Stock in 1951, based at Pittsworth. He found soil conservation work with farmers thoroughly satisfying, laying out and supervising construction of more than 150 km of contour bank erosion-protection systems – some of Queensland's earliest. It was in Pittsworth that he met and married Lenor Whittaker in 1954. Jim rarely talked to colleagues about his personal life, but in later life described his time in Pittsworth as "wonderful days".

Jim moved back to Queensland Agricultural College (QAC) at Gatton as Lecturer in Agronomy in 1955, expecting to specialise in soil conservation. Unfortunately, staff deaths and losses saw Jim, the 'willing horse', taking on a huge range of subjects in a new three-year diploma course. Over his first 10 years, these subjects included Meteorology, Economic Geography, Soils, Surveying, Botany, Crop Agronomy, Tropical Agriculture, Rural Economics, Principles of Agronomy, and History of Agriculture, plus filling in for Plant Pathology and Chemistry. In addition to Soil and Water Conservation (Field Engineering), he also taught sections of the UQ agriculture course. Despite this course load, in 1968 he completed an external masters degree focused on soil–plant water relations. With the college's long boundary with Lockyer Creek, Jim also became very aware of its continuous healthy flow for 365 days of the year and its deep swimming holes.

A visit to the UK and Israel in 1972 – particularly a six-week Volcani Institute irrigation course and travel from Israel's north to the Negev in the south – left a deep impression on Jim. Large-scale trickle irrigation was being developed, and Israel was 'making the desert bloom' with more efficient irrigation, based on national consensus that water was a valuable community asset, to be rationed and distributed equitably across irrigable soils. It was a vision Jim carried with him to the end of his life. His arguments were dismissed in some quarters as utopian, but few doubted that what he said was based on good science and generous, genuine belief.

Jim built one of the earliest rainfall simulators in Queensland, based on designs seen in Israel. Several of these units were widely used to demonstrate the soil-protection effects of crop residue and were a valuable contribution to Queensland soil-conservation extension efforts in the 1970s and 1980s. At that time, Jim gained great satisfaction from running specialist fourth-year subjects on Soil and Water Conservation for QAC degree courses, maintaining contact with students for years after their graduation. From the mid-1970s most Queensland Department of Primary Industries soil conservation field services staff had undertaken Jim's courses at Gatton.

Jim was awarded the first QAC internally funded research grant to undertake a three-year investigation of irrigation water use on college properties. By then, overuse of Lockyer Valley aquifers was becoming obvious, and many irrigation farmers were running dry with dire financial consequences. In response, Jim designed some of the first flood-harvesting systems, with ring tanks and cheap, high-capacity, low-head centrifugal pumps providing an alternative irrigation water supply. Many hundreds of these structures now make a major contribution to the productivity of the Darling Downs and Lockyer Valley. Much of this work was done in association with the Lockyer Water Management Association and Crowley Vale Water Board, of which Jim was a founding member.

Jim was active in the Australian Institute of Agricultural Science and Technology, and was its Queensland President in the 1980s. In the 1990s he ran his own small farm at Crowley Vale, growing small crops and lucerne, and delivering produce to customers in his old Holden Ute which was known locally as the "Grey Ghost". Always the innovator, Jim was an original paddock-to-plate small-scale farmer.

For nearly 75 years, Jim Galletly was associated with the Gatton region, the college and its more recent incarnation as a University of Queensland campus. His tireless community service included being District Commissioner for Scouts and

Treasurer of the Churchill Memorial Trust. He worked with the Lockyer District High School committee to fund a grand piano for the hall; led the push to start Meals on Wheels in Gatton; raised funds for the Gatton Senior Citizens Centre; and sang in the Choral Society. He was a member of the Gatton Shire cultural group; the Post-Polio support group; and a life member of the Leukaemia Foundation of Queensland. Several of these activities occurred as part of his involvement with Apex where he was Secretary and President, and then as a member of its 'Walking Stick Club'. Lenor was Jim's constant companion and committed supporter, working together with him in community service clubs and activities throughout their 64-year marriage. Opposite each other on Galletly Road at UQ Gatton are Lake Galletly and Lake Lenor, acknowledging the couple's contributions to the campus.

Jim's persistence over many years resulted in the Lake Apex Park wildlife and recreational area, a major community asset for Gatton. Social justice issues were always important to Jim, who was a long-term member of the Australian Labor Party. In later life he was active in the QAC Past Students Association and became a Freemason.

However, Jim's essential interests were always soil and water. Having observed the Lockyer Creek since 1943, and the irrigation water supply failures of the 1970s–1980s, he felt sure there was a problem with the publicly accepted account of the Lockyer Valley aquifer recharge system. He made this the topic of his PhD thesis, undertaken after retirement and completed at the age of 80, as one of the most senior UQ PhD graduates.

Jim's 2007 thesis on baseflow analysed many years' creek flow and rainfall data to demonstrate the existence of large and previously unrecognised upland basalt aquifers, and their role in maintaining baseflow. He also identified the link between baseflow and alluvial aquifer recharge, and the likely mechanism of baseflow failure and aquifer exhaustion in the 1970s–1980s.

Jim's important PhD findings in the Lockyer Valley potentially provide answers to other catchments in eastern Australia, including those of the Murray-Darling Basin, which are also facing serious problems. Many have headwaters in volcanic uplands, with springs and waterfalls providing baseflow to catchment creek headwaters. And perhaps, as in the Lockyer Valley, they play a vital role in maintaining downstream aquifers.

Jim was a tireless writer to editors, water boards, authorities and commissions of inquiry, urging action on Australia's emerging water crisis, repeatedly emphasising the simple principles:

- Understand your catchment and basin; then they can be managed sustainably.
- To be sustainable, the volume of water extracted from any basin must not exceed the volume available to replenish it. If more water is taken, the system will keep failing.
- Streams and groundwater are intricately linked within a basin, but groundwater extraction is rarely measured or metered in Australia. You can't manage what you don't measure.
- Water planning, allocation and use in every Australian catchment and basin must be based on sound scientific knowledge and principles, and accurate field studies and measurement, rather than simulation modelling.

Lake Galletly, University of Queensland, Gatton.

Jim died in Toowoomba on 5 June 2020, supported by his three children – Tony, Kay and Sue and their families. His long and productive life had touched many people and communities. A humble, genuine, serious-minded but practical man, inexhaustible and doggedly focused on the task, Jim's was a life of service – doing the thoughtful, right, fair and generous thing for his family, students, employers, community and the environment. One of Australia's greatest water champions, he will be remembered as someone unafraid to speak his mind, thoughtful, enquiring, idealistic, hard-working, and deeply concerned for both his local and broader communities.

Authors

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